A COMPARATIVE STUDY OF SUPERCONDUCTING COMPOSITE CONDUCTORS WITH FILAMENTS OF A-15 COMPOUNDS*

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Abstract

Composite superconductors consisting of fine filaments of Nb_3Sn, V_3Ga, and V_3Si in bronze matrixes (Cu-Sn, Cu-Ga, and Cu-Si, respectively) have been made by the solid state diffusion method. The conductors have identical geometry and consist of 19 filaments approximately 25 μm diameter filaments in a 0.25 mm diameter wire. The superconducting properties of these composite wires are compared as well as their susceptibility to mechanical damage.

Introduction

At present the use of composite wires, which consist of fine superconducting filaments in a high conductivity matrix, is standard practice in the application of superconductors to the generation of high magnetic fields. It is a well established fact that such composites offer better stability and lower losses in devices with time varying magnetic fields.[1,2] Recent and interesting developments in the area of superconducting materials indicated that it is possible to produce fine filament composites with the superconducting A-15 compounds, Nb_3Sn,[3,4] V_3Ga,[5,6] and V_3Si.[7] Such composites have higher critical temperatures, T_c, magnetic fields, H_{c2}, and current densities, J_c, than the presently used Ti-Nb alloys. However, all of these compounds are very brittle and easily damaged by bending. In this paper the susceptibility to mechanical damage caused by bending is compared for these composites as well as their critical temperatures and the dependence of the critical current on magnetic field. The composites were made by a solid state diffusion method.[3,5,6,7] The results for a Nb_3Sn composite, which was produced by a surface diffusion method,[4] are included also for comparison. Since both of the processing methods have been described earlier, they are not described in detail here.

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Critical Temperatures and Critical Current Densities

In general, the critical temperature of a superconducting compound is sensitive to the heat treatment and it was found that proper heat treatments were required to obtain optimum critical temperatures for each type of wire. Representative values of T_c are shown in Fig. 1 as a function of heat treatment time and temperature. In the case of the Nb_3Sn composite the critical temperature is compared for wires made by the two different processing methods. The open marks indicate that the compound was formed by heating Nb in a Cu-Sn matrix (the solid diffusion method), and the closed points denote T_c for a wire which was made by diffusing Sn into a composite of Nb in Cu and then heat treating to form Nb_3Sn (the surface diffusion method). Although the composites, made by the surface diffusion method, exhibited broader transition temperatures than the wires made by the solid diffusion method, the half resistance temperature was almost identical for both wires.

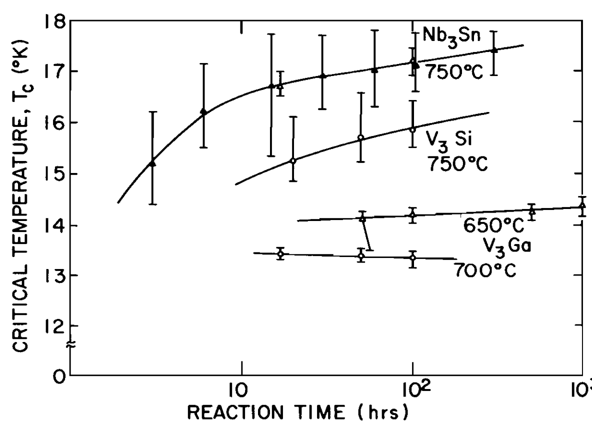

Fig. 1. Examples of the variation of the critical temperature, T_c, with heat treatment for Nb_3Sn, V_3Ga, and V_3Si composite wires.

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In the case of the Nb_3Sn and V_3Si composites, the temperature of the heat treatment does not appreciably affect the T_c for wires with identical thickness of superconductor.[4,7] In the case of V_3Ga, however, it was observed that the lower the heat treatment temperature the higher the critical temperature,[6] possibly showing the effect of increased ordering in the V_3Ga crystal structure.

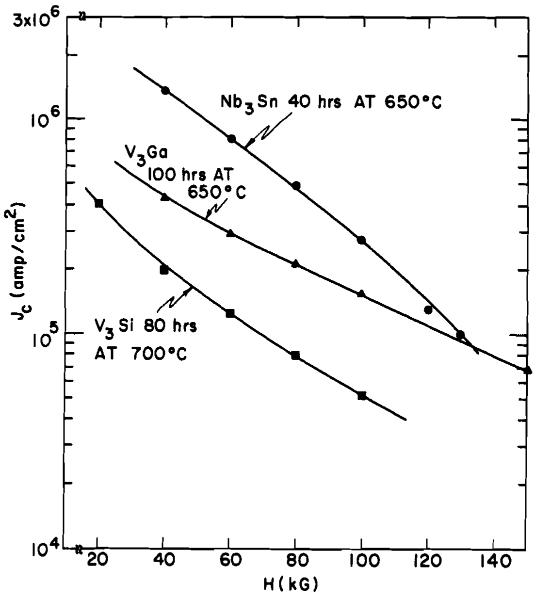

Fig. 2. Typical values of the critical current density, J_c, as a function of applied magnetic field, H, for Nb_3Sn, V_3Ga, and V_3Si composite wires.

As mentioned above, there are some characteristic differences in the dependence of T_c on the heat treatment among the composite wires. The critical temperatures of the all composite wires were, however, within one half of a degree of the bulk values for the respective compounds when properly heat treated.

The critical current density, $J_c(H)$, as a function of applied magnetic field is also one of the most important properties of the superconductor. Since these compounds have higher critical magnetic fields than NbTi alloys, the composite wires could be used for the generation of higher magnetic fields provided their critical currents are sufficiently high. A comparison of $J_c(H)$ for Nb_3Sn, V_3Ga, and V_3Si is summarized in Fig. 2. The general behavior of $J_c(H)$ for the composite wires is comparable with or higher than that for the respective superconducting tapes. From Fig. 2 it can be seen that Nb_3Sn has the best J_c below 130 kG while V_3Ga is better above 130 kG.

Susceptibility to Mechanical Damage

As mentioned earlier, A-15 compounds are very brittle and are easily damaged by bending and handling. However, to be useful for magnet construction the composite wires must be able to be bent at quite small radii without degradation of their superconducting properties. In order to test their capability to withstand handling, "bending tests" were performed for all the composite wires. A bending test consists of bending a wire around a mandrel, straightening it, and remeasuring the critical current at 4.2°K and 40 kG. The critical current was defined as that current which gave rise to a voltage drop of 1 μV across a 3 cm length of the specimen. In most cases, current sharing between the superconductor and the matrix was observed as the superconducting to the normal transition occurred. This current sharing is shown in Fig. 3 by the increase in sample voltage as the quench current is approached. When the critical current of a wire is high ($\gtrsim$20 A), the transition is very abrupt and it is not possible to observe the current sharing between the filaments and the matrix because of the high matrix resistivity. Also, when there is no current sharing, "training" in the critical current is usually observed. In this case, the critical current of the wire is defined as the maximum value of the current after several transitions. A summary of the effect of bending on the current carrying capacities of the composite wires is shown in Fig. 4 for V_3Ga and Nb_3Sn, and Fig. 5 for V_3Si. When the superconducting filaments and the matrix can share the current at the transition, the degradation of J_c with decreasing bending diameters is usually consistent as seen in Fig. 4a, 4c, and 5. When the transition is abrupt and considerable current training takes

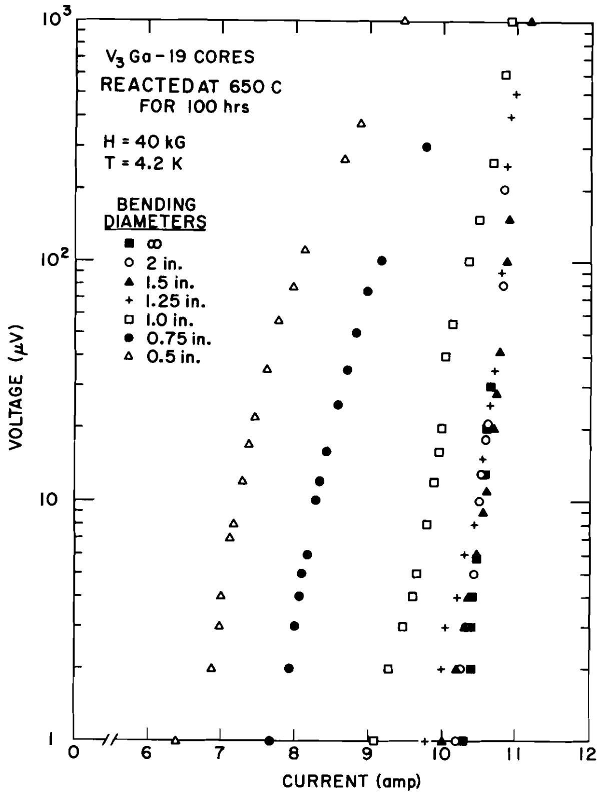

Fig. 3. An example of the variation of the voltage vs current relationship of a V_3Ga composite subjected to successively smaller bending diameters.

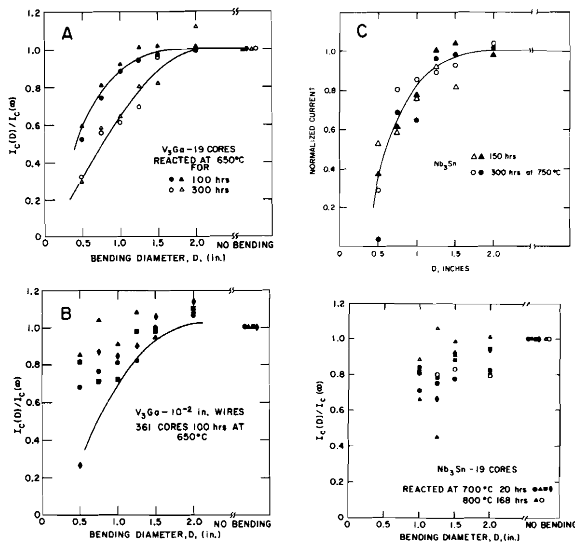

Fig. 4. Critical current degradation as a function of bending diameter. a) 19 cores V_3Ga, (thickness: ~1 μm and ~1.5 μm) b) 361 cores V_3Ga, c) 7 cores Nb_3Sn made by the surface diffusion method, d) 19 cores Nb_3Sn made by the solid state diffusion method.

place, however, the degradation of J_c with bending is very erratic. In some cases, J_c for a particular bending diameter exceeds the J_c value for the previous larger bending diameter. This is shown in Fig. 4b and 4d. The individual marks indicate the J_c variation of a given wire on successive bends. It was also noted that the degradation of J_c was more pronounced for the thicker layers of the compounds as shown in Fig. 4b and Fig. 5. This was especially evident for V_3Si and is thought to be due to the formation of a V_5Si_3 layer in addition to the V_3Si.[7]

While wires with 19 cores as shown in Fig. 6c and 6d are convenient for investigating the superconducting properties of the composites, such a conductor geometry is not suitable for a practical conductor. In order to study the possibility of a difference in the bending characteristics of a wire with much finer filaments, a 351 core V_3Ga composite was made by reducing a group of 19 of the 19 core wires to form the conductor shown in Fig. 6a and 6b. Both J_c and T_c for this composite were the same as those observed for the 19 core material when given the same heat treatment. A comparison of the effect of bending on these wires is shown in Fig. 4a and 4b. Within the scattering of the data points, the degradation due to bending is the same for the 361 and the 19 core composites. In addition the possibility of a difference in the bending behavior of wires which were processed by the solid state diffusion and the surface diffusion methods was examined. For the case of Nb_3Sn composites the results are shown in Fig. 4c and 4d which show the effect of bending on the wire made by the surface diffusion (Fig. 4c) and the solid state diffusion methods (Fig. 4d), respectively. This comparison indicates that

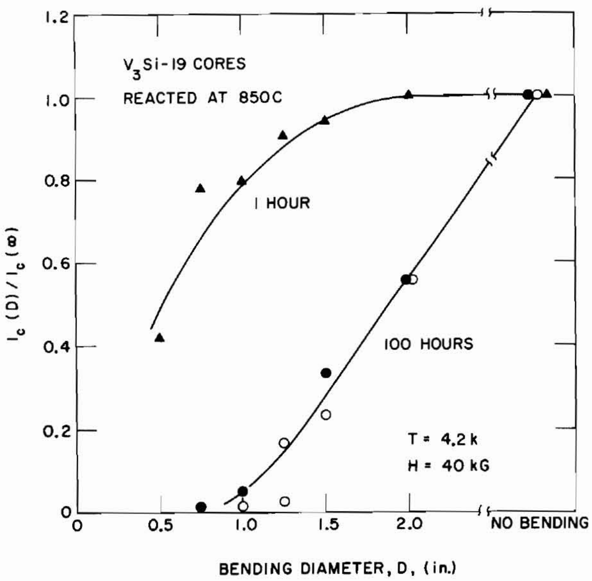

Fig. 5. Critical current degradation as a function of bending diameter for two thicknesses (~1 μm and ~2 μm) of V_3Si.

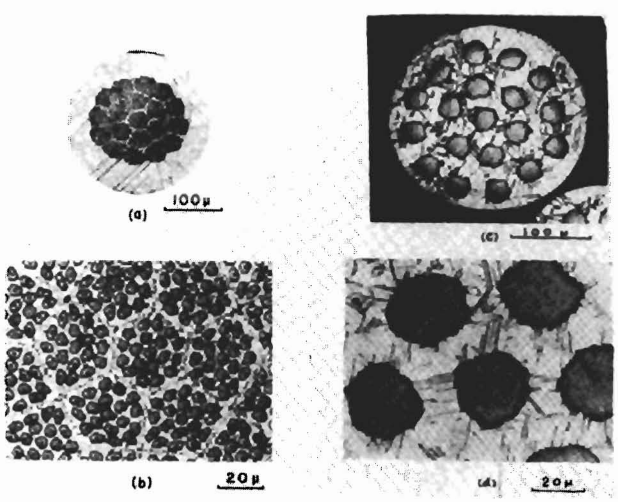

Fig. 6. Cross-sectional views of (a,b) 361 cores and (c,d) 19 cores V_3Ga composite wires.

the composites made by the solid state diffusion method are more susceptible to mechanical damage. However, this point should be further investigated using wires of more nearly identical current since the sample made by the solid state diffusion method exhibited extreme "training" and accurate measurements of the bending effect were difficult.

Conclusions

In summary, it can be stated that (1) Nb_3Sn and V_3Ga composites are the most promising candidates for a practical conductor material; (2) Nb_3Sn appears to be somewhat more susceptible to mechanical damage than V_3Ga but both compounds are much better than V_3Si which shows extreme brittleness especially in thick layers.

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