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Composite superconductors of Cu(Sn)/Nb(Al)

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Using powder–metallurgical techniques, superconducting ribbons and wires have been prepared, consisting of various compositions of randomly-arranged Nb(Al) filaments embedded in a Cu(Sn) matrix. Typically, the transition temperature of this group of new composite superconductors is 15.8 to 17.7 K and the critical current density at 4.2 K and zero field is of the order of 10^4 A cm^{-2}.

1. Introduction

Large-scale application of high transition-temperature (T_c) superconductors with the β–W structure has come close to reality ever since the discovery of the bronze diffusion process in the Nb–Sn and V–Ga systems [1, 2]. The conventional approach to fabricating such superconductors into multifilamentory configuration has been by inserting Nb or V rods into prefabricated bores in a Cu(Sn) or Cu(Ga) matrix alloy respectively. After cold-working the composites down to desirable size, and interfacial layer of Nb_3Sn or V_3Ga is then formed at the surface of Nb or V with a final heat-treatment.

Recently Tsuei *et al.* [3, 4] reported a modified bronze process which had the advantage of being much more economical. The essential feature of Tsuei's method was to melt the constituents (either Cu–Sn–Nb or Cu–Ga–V) together as the first step, followed by the processes of wire-making and final annealing, which remained the same.

Due to metallurgical limitations, the work on composite superconductors has been confined to Nb–Sn–Cu and V–Ga–Cu systems only. An attempt to form random Nb_3Al and Nb_3(Al, Sn) filaments in a Cu-matrix using powder-metallurgical techniques is reported here. The basis of this study was the following experimental results.

(i) In equilibrium, Nb dissolves more than 10 at.% Al [5]. At high quenching rate, the body-centred cubic (b c c) Nb-rich solid solution can be extended up to 50 at.% Al [6].

(ii) Although the intermetallic compounds in the Nb–Al system, Nb_3Al and Nb_2Al, are extremely brittle, the b c c Nb solid solutions are hard but workable.

(iii) Nb, together with Ta and V, absorbs a large amount of hydrogen at moderate temperatures (300 to 400° C) and becomes subsequently embrittled. Such hydrogen-embrittling tendency remains strong in the b c c Nb(Al) solid solutions. Furthermore, the absorbed hydrogen can be completely removed from the host alloy in high vacuum at slightly higher temperature (500° C). Thus powders of desired particle sizes can be readily made for Nb-rich solid solutions with various Al contents through the hydrogen absorption and desorption processes.

(iv) The T_c of the b c c phase of Nb–25 at.% Al retained by fast-quenching, is only about 3 K. But after being converted into the β–W structure with proper annealing, its superconducting characteristics are highly compatible with those of the Nb_3Al phase prepared by other methods [6].

(v) According to the literature, the substitution of Al with Sn in Nb_3Al or vice versa does not have much adverse effect on T_c [7–9]. It seems reasonable to assume that the critical current capacity of the pseudobinary β–W phase of Nb_3(Al, Sn) would also be compatible with those of Nb_3Al and Nb_3Sn, because the flux-pinning mechanism is not expected to reduce drastically when a third element is introduced into a binary phase.

2. Experimental procedures

The starting Cu(Sn) powders (particle size < 40 μm) with a nominal composition of 5.6 at.% Sn (10 wt%) were purchased from Eckart–Werke.

Nb–Al alloys were first prepared in the b c c phase and then powdered after hydrogen-embrittlement. Powder mixtures of proper ratio of the constituents were pressed (8 to 10 tons cm^{-2}) into pellets of 0.5 to 0.8 cm diameter and 0.5 to 1.0 cm long. Before cold-working, a flash sintering (a few minutes at 700° C) was often needed to provide sufficient mechanical strength to the composite material.

Swaging and rolling were both used to deform the pellets into wires and ribbons. During cold-working, intermediate stress-relief was required for composites with low Cu(Sn)/Nb(Al) ratios. For all wires and ribbons a uniform final heat-treatment was given at 800° C for 15 h.

The T_c and critical current density (J_c) measurements were carried out using a standard four-probe technique. In a majority of cases, liquid hydrogen was used as coolant. The International Practical Temperature Scale of 1968 for the vapour pressure of hydrogen was adopted for the calibration of temperatures [10]. Throughout the present investigation the J_c was designated when a field strength of 1 $\mu V\,cm^{-1}$ was developed between the two voltage leads.

3. Results and discussion

There are a number of factors that affect the properties of multifilamentary superconductors. Fig. 1 illustrates some of them. Of the cold-working processes used, the present experience indicates that the superconducting characteristics of wires and ribbons produced by rolling are better than those produced by swaging. This observation is not really surprising because the rolling process is expected to produce more uniaxial deformation and hence better formed superconducting filaments in the end products. From this point of view processes of extrusion and drawing would also be suitable.

Furthermore, it was also noted that a minimum area reduction factor of 100 was necessary to bring the electrical resistance of the entire length of wire or ribbon below detectable levels. This condition is clear in view of that the parallel but discontinuous superconducting filaments would have to be brought in close proximity in order to reduce the residual resistance that might have existed in the normal region between the adjacent filaments.

Another crucial factor which is closely related to the behaviour of this type of composite superconductors is the ratio of Cu(Sn)/Nb(Al) in the starting material. If this ratio is large, there exists substantial residual resistance in the composite conductor even at temperatures much below the T_c of the superconducting segments. However, if it is too small, the composite cannot develop sufficient mechanical strength to sustain the cold-working processes. Through additional experiments this factor can be optimized and controlled.

In general, the T_c of each of the composites prepared in the present investigation was relatively high and sharp compared to the published results

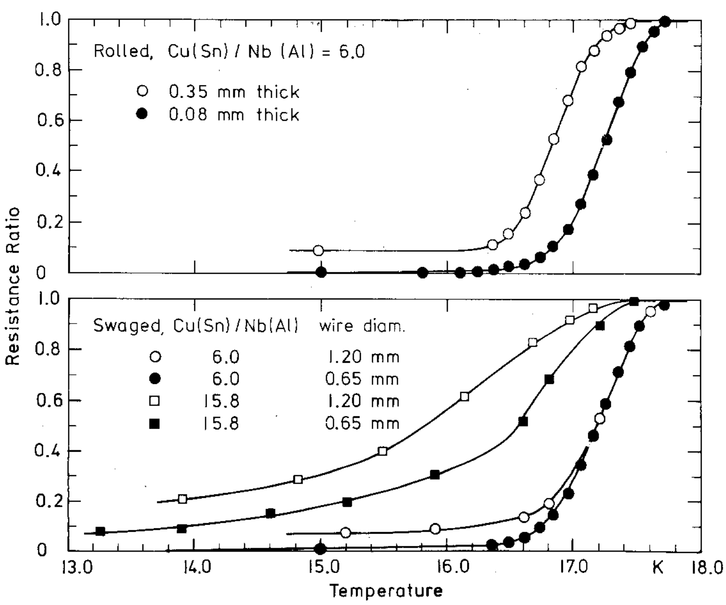

Figure 1 Comparison of superconducting transitions of the Cu(Sn)/Nb(Al) composites after different amounts of deformation and by different cold-working processes (The initial dimension was 8 mm in all cases).

TABLE I Comparison of composite superconductors with randomly distributed superconducting filaments.

Alloy			Wt. ratio Cu(Sn)/Nb	Phys. Dim. (mm)	T_c (K)	J_c ($A\,cm^{-2}$)	Temperature magnetic field		Reference
Cu	Sn	Nb					(K)	(kOe)	
93	2	5	13.23	0.1	11.0–16.5	3×10^4	4.2	30	[11]
93	2	5	13.23	0.1	14.2–17.0	4×10^4	4.2	30	[11]
93	2	5	13.23	0.1	11.0–17.2	2.4×10^4	4.2	30	[11]
88.5	1.5	10	6.24	0.25ϕ	~ 15	2.1×10^4	4.2	20	[12]
88.5	1.5	10	6.24	0.25ϕ	~ 15	1.3×10^4	4.2	30	[12]
83.5	1.5	15	3.93	0.25ϕ	~ 15	1.0×10^4	4.2	40	[12]
83.5	1.5	15	3.93	0.25ϕ	~ 15	0.2×10^4	4.2	80	[12]
*			5.96	0.08	15.8–17.7†	1.0×10^4	4.2	0	Present work
			5.96	0.65ϕ	14.0–17.8†	1.0×10^4	4.2	0	Present work

* Starting material: Nb–5 at.% Al and Cu–5.6 at.% Sn.
† The transition temperature widths were taken directly from Fig. 1, for specimens whose resistances were practically zero at the lower temperature limit.

(Table I). The J_c behaviour in magnetic fields was also reasonable (Fig. 2).

It is clear that there are two main differences between the multifilamentary superconductors prepared by the conventional approach and by Tsuei's method. The superconducting filaments in the former are continuous and uniformly distributed in prearranged positions, while in the latter they are discontinuous and distributed randomly. The discontinuity in filaments undoubtedly becomes the weak link in the overall superconduction of the wire, and causes its J_c value to be two orders of magnitude lower. However, such inferiority is not necessarily insurmountable. If the particle sizes in the starting Nb(Al) material were bigger, longer filaments (and hence fewer discontinuities) along the wire or ribbon could be expected, other conditions being equal. Some exploratory experiments have been attempted regarding this point and the results are shown in Fig. 3. The set of experiments were conducted under identical procedures and conditions except the different particle sizes of Nb(Al) as noted. Encouragingly, the superconducting transition of the specimen with larger Nb(Al) particle sizes was much better defined. If the experimental parameters are optimized and under ideal circumstances the formation of continuous superconducting filaments remains a distinct possibility. This is an important advantage in using powder–metallurgical techniques over Tsuei's original melting approach in which the precipitated Nb particles were invariably small.

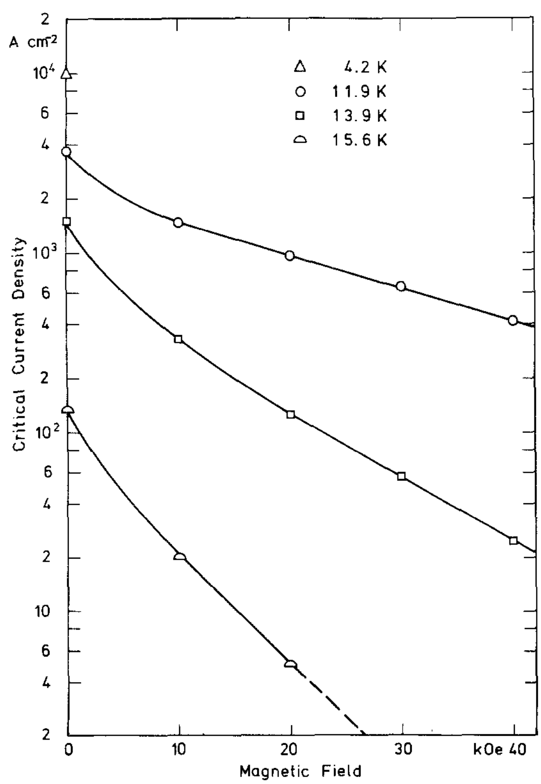

Figure 2 Critical current densities of the Cu(Sn)/Nb(Al) composites in the temperature range that can be reached by using hydrogen as a coolant. The complete transition width of this specimen was 15.8 to 17.7 K.

In conclusion, there are several factors in the preparation process which can effectively influence the characteristics of the randomly-distributed superconducting filaments in a Cu-matrix. Namely,

(1) The ratio Cu(Sn)/Nb(Al) or other combinations.

(2) Characteristics of starting material; particle size, surface condition, etc.

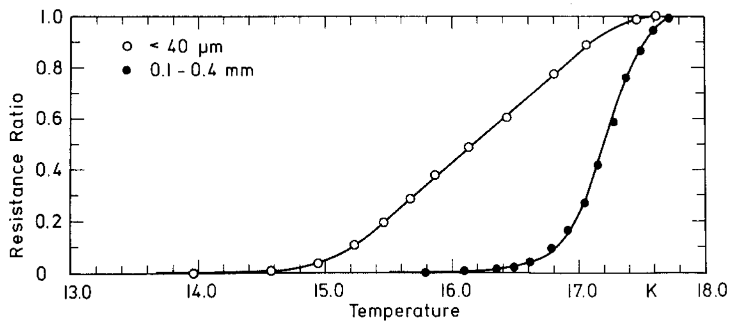

Figure 3 Superconducting transitions of two Cu(Sn)/Nb(Al) composites with different particle sizes in the starting material. Both specimens were rolled to an area reduction of ~ 100. The Cu(Sn)/Nb(Al) ratio was also the same at 6.0.

(3) Wire-making process; drawing, or rolling, or swaging;

(4) Total area reduction.

(5) Intermediate heat-treatment

(6) Last-stage annealing

Undoubtedly, the performance of this type of multifilamentary superconductors will be improved by optimizing some of these factors. To fully explore the potential application of this type of material, further investigation is needed.

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