SUPERCONDUCTING AND MECHANICAL PROPERTIES OF *IN SITU* FORMED Cu–V₃Ga COMPOSITES*

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INTRODUCTION

V₃Ga-based superconducting composites exhibit higher critical current densities at high fields (12 to 20 T) than any other practical superconductor, including Nb₃Sn. Their low-field performance is limited by the difficulty of producing the material with sufficiently small grain size and not by its intrinsic properties [1]. Two recent reports on model V₃Ga-based conductors have demonstrated that these problems can be substantially alleviated. One successful approach consisted of reacting composites at lower temperatures (≤500°C) using a so-called modified bronze technique [1,2]; the other relied on manipulating the size and shape of V₃Ga grains by the addition of ternary elements [1].

High critical current density over a wide range of magnetic fields is, of course, a prerequisite for most practical applications, but by itself it is not sufficient. A practical superconductor should also be stable, relatively insensitive to the applied stress and strain, and for many applications, should have low losses in alternating fields. These requirements usually necessitate a multifilamentary configuration, whereby thin superconducting filaments are imbedded in a high-conductivity matrix material. The present state of the art in producing multifilamentary V₃Ga composites, to a great extent, relies on techniques developed for Nb₃Sn-based conductors.

One of the more serious problems of Nb₃Sn multifilamentary composites, which considerably slowed their development for large-scale applications, is their pronounced sensitivity to applied stress. Although currently available Nb₃Sn conductors have greatly improved mechanical properties, it is premature to conclude that a solution has been reached for V₃Ga conductors as well. The tendency for crack formation in brittle V₃Ga filaments in practical multifilamentary conductors is likely to be more pronounced than in Nb₃Sn-based composites and, therefore, deserves special attention.

Recently developed *in situ* Cu–Nb₃Sn composites have excellent mechanical properties [1–7] and critical current densities comparable to those of the best

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conventional composites \cite{4,5,8-10}. Along with the powder-metallurgically processed composites \cite{11-14}, these new materials show realistic promise for potential practical applications and can now be produced in large quantities also \cite{15}.

Recently the authors reported on \textit{in situ} formed Cu–V₃Ga composites with excellent critical properties \cite{16}. In this paper, their performance is compared with that of \textit{in situ} Cu–Nb₃Sn with a similar microgeometry, and the effect of the applied stress on their critical current density and upper critical field is reported.

**EXPERIMENTAL PROCEDURES**

The samples used in this study were prepared by induction melting bulk copper and vanadium in a water-cooled copper crucible. The cast ingot, about 10 mm in diameter, with a nominal composition of Cu–20 vol.% V, was then swaged and cold-drawn to various reductions in the cross-sectional area without intermediate annealing. Shorter pieces of wire were coated with gallium by conventional techniques and annealed in a vacuum for various lengths of time at temperatures ranging from 450 to 600°C.

Critical current density, \(J_c\), and the superconducting transition temperature, \(T_c\), were measured resistively, using the standard four-probe technique. The upper critical field, \(H_{c2}\), was determined by obtaining a resistive transition while sweeping the field in a Bitter-type solenoid capable of producing up to 23.6 T. Both \(J_c\) and \(H_{c2}\) were also measured as a function of stress up to 1.06 GPa. The small magnet bore limited the sample length to about 14 mm and the voltage-lead spacing to 5 mm. \(J_c\) was defined as the current density at which the potential drop across the voltage leads exceeded 1 \(\mu\)V.

**RESULTS AND DISCUSSION**

The microstructure and the deformation mode during the mechanical reduction of the two-phase Cu–V alloys were found to be very similar to those observed in other f.c.c.–b.c.c. \textit{in situ} formed composites, such as Cu–Nb \cite{17}. A characteristic feature of all these materials is a high density of very thin ribbonlike filaments (Fig. 1) in intimate contact with the matrix material. Although the filaments are discontinuous in composites below the critical percolation limit, they can have an aspect ratio of 10\(^6\) or more, depending on the overall composite reduction. Many physical properties of such composites (e.g., mechanical strength and electrical and thermal conductivity) are indistinguishable from those of continuous-filament materials with comparable filament thickness and spacing.

Figure 2 shows the field dependence of the overall critical current density for a 0.25-mm-diameter Cu–20 vol.% V composite containing 12.4 wt.% of gallium. For comparison, \(J_c\) of a Cu–Nb₃Sn \textit{in situ} formed tape \cite{18} with a comparable cross-sectional area and niobium volume fraction (0.182) is shown on the same graph. The annealing temperatures were 590°C and 560°C, respectively. The superior performance of Cu–V₃Ga composites in fields greater than about 10 T is in agreement with similar studies made on conventional conductors. Another attractive feature of Cu–V₃Ga \textit{in situ} composites is their exceptionally high \(T_c\) and \(H_{c2}\) \cite{16}. In contrast to \textit{in situ} formed Cu–Nb₃Sn conductors, where both critical parameters are considerably lower than in a bulk compound, the corresponding values for \textit{in situ} V₃Ga of 15.5 K and 22.4 T are among the highest reported in the literature \cite{19}.

Critical properties of Nb₃Sn-based conductors are known to depend sensitively on the stress state of the composite. The negative effect of the compressive stress
exerted on the filaments by the surrounding matrix can be substantially reduced by prestressing in situ composites to about 60 to 80% of their ultimate tensile stress [18]. Typical results for this procedure on Cu–Nb$_3$Sn composites are shown in Fig. 2. The increase in $J_c$ is particularly pronounced at high fields and is due to a permanent increase of $H_{c2}$ of 1 to 2 T.

Fig. 2. Comparison of the high-field critical current densities in Cu–V–Ga and Cu–Nb–Sn in situ composites with comparable cross-sectional area and filament volume fraction.
To investigate the stress sensitivity of Cu–V$_3$Ga in situ composites, particularly in the high-field region, a new stress probe was constructed for use with a small-bore (23.6-T) Bitter-type solenoid. $J_c$ was measured as a function of applied stress in fields up to 21 T, and $H_{c2}$ was determined directly by observing the resistive transition while sweeping the field. Figure 3 shows the stress dependence of the critical current density for a few selected fields. $J_c$ remains constant within the experimental error up to about 200 MPa and then starts to decrease gradually. The relative change increases with the field and at 1 GPa amounts to 17 and 42% at 14 and 20 T, respectively. However, no permanent degradation was observed even for stress levels in excess of 1 GPa. In fact, after releasing the stress, $J_c$ was found to increase 8 to 15% over the original value, depending on the field.

The upper critical field, defined by the onset of the normal-to-superconducting transition (90% of the sample normal-state resistivity), decreased by only 0.1 T when the sample was subjected to the maximum stress of 1.06 GPa. At the same time, the transition width, $\Delta H_{c2}$, gradually increased from 0.8 T ($J = 30$ A/cm$^2$) in the unstressed state to 1.0 at 1 GPa. These observations are in broad agreement with the results of a similar study by Fiehley, Roberge, Foner, McNiff, and Schwartz [20] and are also consistent with the measured strain dependence of $T_c$ in V$_3$Ga and other A15 compounds [21].

In contrast to numerous experimental studies of stress effects in Cu–Nb$_3$Sn wires with continuous filaments, very little is known about the stress behavior of similar Cu–V$_3$Ga composites. Gubser, Francavilla, Howe, and Jones [22] reported degradation of $J_c$ above about 300 MPa in a model V$_3$Ga-composite conductor where only a thin layer of vanadium filaments had reacted with gallium to form the A15 compound. Other work has demonstrated that the irreversible degradation of $J_c$ in Nb$_3$Sn conductors is caused primarily by crack formation in the brittle A15 filaments.

![Graph showing $J_c$ vs. applied stress for different fields.](image)

Fig. 3. Overall critical current density, $J_c$, vs. applied stress, $\sigma$, measured in the 14 to 20 T field range, for a typical Cu–V–Ga in situ formed composite.
This raises serious doubts whether bronze or modified bronze techniques, which were used to produce model superconductors with remarkable $J_c$ characteristics, can be successfully applied to practical superconducting composites with a large number of small, fully reacted filaments. High gallium concentration in the matrix leads to rapid work-hardening, which is accelerated by the presence of filaments, and therefore, intermediate annealings during composite reduction are necessary. However, the annealing temperature for copper and copper solid solutions (450 to 500°C) is already in the range in which the $V_2$Ga compound can be formed in the presence of a copper matrix [1]. (In the authors’ study of in situ Cu–$V_2$Ga composites, traces of the A15 compound were found at temperatures as low as 400°C.) Subsequent further reduction of the composite is expected to lead to breaking up of the brittle surface layer and, almost certainly, to poor performance under applied stress. If this turns out to be the case, the in situ technique described in this paper should be considered an acceptable alternative solution for fabrication of high-strength, multifilamentary $V_2$Ga composites.

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