INTRODUCTION

Several different processes are presently under investigation for the preparation of multifilamentary superconducting wire having filament dimensions in the 0.1-μm region. Tsuei, Suenaga, and Sampson \cite{1,2} pioneered work in the development of superconducting composites by controlled precipitation in the early 1970's, but the performance characteristics at that time were not adequate for industrial development. More recently, Harbison and Bevk \cite{3}, Foner, McNiff, Schwartz, Roberge, and Fihey \cite{4}, and Verhoeven, Finnemore, Gibson, Ostenson, and Goodrich \cite{5} have made important advances in the casting and fabrication technique and have developed composites with performance characteristics sufficiently attractive that now they may be suitable for large-scale magnets. At the same time that these precipitation processes were being developed, there also was considerable effort to develop powder metallurgy techniques for composite preparation. Work by Flüktiger, Foner, McNiff, Schwartz, Adams, Forman, Eagar, and Rose \cite{6} and Freyhardt, Bormann, and Bergmann \cite{7} have shown that the powder metallurgical composites have very attractive critical-current densities. In the early work for all of these processes, research centered on Nb₃Sn-Cu composites, but it is clear that the same procedures can be used on V₃Ga-Cu composites. Bevk, Habbal, Lobb, and Harbison \cite{8} and Fihey, Roberge, Foner, McNiff, and Schwartz \cite{9} have demonstrated excellent critical-current behavior above 12 T and very good mechanical properties. Each of these processes shows considerable potential, and it is important to develop those that are best suited for industrial-scale production.

With the introduction of consumable electrode arc-casting techniques \cite{10} for the preparation of large billets of dendritic Cu-Nb alloys, there seems to be a realistic chance that a new family of Nb₃Sn-Cu composites \cite{5} can be developed for large-scale magnets in the 8- to 14-T range. Briefly stated, this process for fabricating superconducting wire involves (1) casting of large billets of Cu-Nb alloy to give a homogeneous array of long Nb dendrites, (2) extruding the billets to a long rod form, and (3) drawing the rod into wire. The tin can be introduced either at the extruded

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rod stage as a core in the rod [11] or by tin plating the final wire. Industrial-scale processes are already fairly well developed for the extrusion, drawing, and tin-introduction steps, but the casting of these dendritic alloys is relatively new and will be discussed in some detail here. There has been a clear demonstration that 10-kg billets, which are 5 cm in diameter and 60 cm long, can be cast with suitable dendrite homogeneity and morphology [10]. This work is still in the development stage, but one should be able to raise the diameter of the casting to 15 cm to give 100-kg billets.

In this paper, a review is given of the development of large-scale casting procedures for the dendritic Cu–Nb alloys that are suitable for wire fabrication. A discussion is given of the performance characteristics of the resulting composite wire and special emphasis is placed on a series of experiments designed to produce materials that show high tolerance to bending strain.

**EXPERIMENTAL PROCEDURES**

In the preparation of composites for large-scale magnets, it is very important to maintain a homogeneous distribution of niobium dendrites throughout the original casting. During the early stages of development of this long dendrite process, castings were made by melting appropriate quantities of copper and niobium at 1850°C and pouring the liquid into a water-cooled chill mold in a casting apparatus similar to those discussed previously [5,11]. This process gave excellent dendrite formation in 3-kg castings and the performance of the resulting wire compared favorably with commercial multifilamentary wire [11].

At the same time these chill-casting procedures were being developed, Verhoeven, Schmidt, Gibson, Ostenson, and Finnemore also initiated a series of experiments to utilize consumable electrode arc-casting techniques to prepare the dendritic Cu–Nb alloys [10]. In this process, the electrode was composed of a 1.2-cm-diameter niobium rod and a 2.86-cm-diameter concentric copper tube. A standard water-cooled chill mold with a 0.62-cm-thick graphite liner was used to contain the ingot. The strike pad at the bottom of the mold was a 0.62-cm-thick piece of Cu–Nb alloy with a few centimeters of Cu–Nb turnings to help initiate the spark. After an arc had been struck, the copper in the electrode melted, ran down over the niobium and alloyed with it, and eventually dripped into a pool in the mold. For these 5-cm-diameter castings, good results were obtained by lowering the electrode at a rate to maintain a constant arc voltage of 26 to 27 V and a current of about 1 MA. The molten pool of liquid in the mold was typically 5 cm deep. The graphite sleeve reduced the heat flow in the radial direction to the chill mold and the solid–liquid interface advanced as a nearly horizontal front.

In the first pass of a casting, there normally are a few millimeter-size niobium-rich particles that do not dissolve and form a good dendrite structure. To provide the needed homogeneity, the casting is rod rolled to approximately 4 cm in diameter, and a second pass is made in the arc caster. After two passes, there is a well-formed homogeneous array of niobium dendrites (shown in Fig. 1) across the entire billet. A photograph of these dendrites at higher magnification has been presented elsewhere [10]. Segregation is not a major problem for these 5-cm-diameter castings; the ingot ranges from 19.5 to 20.5% Nb in the radial direction and from 19 to 21% Nb in the vertical direction.

The dendrites for the arc-cast material are more coarse than for the chill-cast material, and they tend to be somewhat shorter. Typically they are 5 μm in diameter and 30 to 100 μm long. After the billet has been extruded to a 1.25-cm-diameter