Progress in Superconducting Performance of Rolled Multifilamentary Bi-2223 HTS Composite Conductors

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Progress in Superconducting Performance of Rolled Multifilamentary Bi-2223 HTS Composite Conductors

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Abstract—Significant enhancements in critical current densities in rolled multifilamentary Bi-2223 HTS composite conductors have been achieved using the powder-in-tube (PIT) technique. At 77 K and self field, oxide critical current densities (Jc) of 55 kA/cm², overall or engineering critical current densities (Jeo) of 15 kA/cm², and critical currents (Ic) of 125 A have been achieved in different rolled multifilamentary composites. Progress in achieving such high electrical performance is believed to stem in part from an improvement of grain connectivity by reducing weak links. The Jc dependence on magnetic field (B) and the degree of c-axis texture of these high quality conductors has been investigated at various temperatures. Our results also demonstrate that the critical current retention in magnetic field can be independently controlled from the self field critical current density, suggesting that flux pinning improvements and weak link reductions can be separately engineered into Bi-2223 composites fabricated using manufacturable processes.

I. INTRODUCTION

A tremendous amount of effort has been made to improve the critical current densities of commercially interesting Ag sheathed Bi-2223 HTS multifilamentary composites. For rolled multifilamentary composites, Jc values in the range of 40 to 44 kA/cm² at 77 K and self field have been reported [1] - [2]. In contrast, Jc values of 50 to 69 kA/cm² have been reported for pressed monofilamentary samples, [1], [3] - [5]. Although the Jc performance of the pressed monofilaments is higher than that of the rolled multifilaments in these previous works, there are compelling reasons to further pursue the latter option. Rolling is a scalable and practical process for making long and continuous lengths of HTS conductor. Moreover, the strain tolerance of multifilamentary composites is superior to that of monofilamentary composites. As a final consideration for the practical use of HTS wire, high Jc and Ic performance is required across long lengths in a magnetic field.

To enhance the self field Jc of the Bi-2223 composites, the connectivity between grains must be improved by reducing the number of weak links. A high degree of c-axis texture and clean grain boundaries are the most effective means of mitigating weak links [5] - [8].

Due to the relatively poor flux pinning of current generation Bi-2223 composites, their Jc decreases markedly in high magnetic fields as temperature increases. Therefore, application of Bi-2223 conductors in high magnetic fields is currently limited to low temperatures. To enhance the in-field Jc of Bi-2223 composites, improvements in the capacity to pin magnetic flux, either by enhancing electronic coupling between Cu-O layers or introducing appropriate defect structures, must be made. The introduction of splayed columnar defects, dislocations, and secondary phase precipitates are thought to enhance flux pinning [9] - [11]. In addition, coupling may be modified via intrinsic doping effects [12]. Recently, Parrell et al. [8], [13] reported that slow cooling during the final heat treatment improves both flux-pinning and connectivity of Bi-2223 composites.

In this article, we report new levels of Jc, Je, and Ic performance for laboratory scale, rolled multifilamentary conductors (< 1 meter lengths). In addition, the Jc(B,T) dependencies have been characterized in magnetic fields up to 10 T at temperatures between 4.2 and 77 K. Finally, we provide an interpretation of the enhanced self field and in-field performance in the context of connectivity and ‘effective’ flux pinning.

II. EXPERIMENTAL

Multifilamentary composites were fabricated using the powder-in-tube technique. The stoichiometry of our precursor powder is Bi₁.₉Pb₀.₃Sr₁.₆Ca₂.₆Cu₃.₁. Sequential thermomechanical processing in which each iteration consists of a rolling plus a heat treatment sequence was used to promote Bi-2223 phase formation, texture, and densification.

Transport critical current (1 μV/cm) measurements in different magnetic fields and at various temperatures were
performed using a standard four probe technique. Transport \( J_c \) and \( J_e \) were determined by dividing the \( I_c \) by the total cross-sectional area of the oxide core and conductor, respectively. The dependence of \( J_c \) on the angular orientation of the applied magnetic field was determined using techniques described in [14].

III. RESULTS

A. Progress in \( J_c, J_e, \) and \( I_c \)

In the past year the superconducting performance of our rolled multifilamentary composite conductors has significantly increased. The results of Fig. 1 represent the improvement of laboratory scale Bi-2223 conductors made by a scalable rolling process at American Superconductor Corporation. On average the \( J_c \) results measured at 77 K in self field, has improved about 11 kA/cm² per year over a five year period. Given the complexity of the Bi-2223 PIT process, it is remarkable that the time rate of performance increase for multifilamentary composites made using scalable techniques is approximately linear over an extended period of time. Moreover, it is highly encouraging to HTS wire developers that there is no apparent decrease in the recent rate of improvement indicated in Fig. 1.

The best \( J_c \) performance has now reached the 55 kA/cm² level (77 K and self field) for rolled 85 filament composites. More importantly, the \( J_c \) standard deviation \( \sigma \) of 12 samples is less than 2%. These results represent the first time that the electrical performance of commercially interesting multifilamentary wires has established parity with that of pressed monofilamentary samples [1], [3] - [5]. We have also achieved \( J_e \) values (77 K and self field) of 15 kA/cm² (\( \sigma = 0.5 \% \) for 8 samples) in rolled 85 filamentary composite conductors. High current capacity samples with \( I_c \) values of 125 A (\( \sigma = 1.7 \) A) have been measured at 77 K and self-field for 313 filament composite conductors. These high \( I_c \) conductors have \( J_c \) values of 39.7 kA/cm². All of these results are obtained at self field. The true zero field \( J_c, J_e, \) and \( I_c \) values are likely to be at least 10% higher than the self field results [6], [15].

Fig. 2 summarizes the \( J_c(B,T) \) dependencies of one of the high \( J_c \) samples in the B \( || \) tape plane (Fig. 2a) and B \( \perp \) tape plane (Fig. 2b) orientations. At 75 K, \( J_c \) values of 45 kA/cm² in 0.1 T, 32 kA/cm² in 0.3 T, and 15 kA/cm² in 1 T are retained in the B \( || \) tape plane direction. Although the self field \( J_c \) value of this 85 filament conductor is lower than that previously reported for pressed monofilamentary samples (66 kA/cm² at 77 K) [5], its \( J_c \) at 1 T is similar to that of the pressed samples (14.5 kA/cm² at 77 K and 1 T). Our earlier study [1] suggests that this may be due to a smaller fraction of weak links in the rolled samples as compared to the pressed samples. At 64 K and B \( || \) tape plane, the self field \( J_c \) of the sample is 86.5 kA/cm², and 42.3 kA/cm² is retained at 1 T. Even in the B \( \perp \) tape plane direction, the sample has \( J_c \) of 18 kA/cm² and 42 kA/cm² at 0.1 T and 77 K and 64 K, respectively. In addition, the \( J_c \) is 295 kA/cm² at 4.2 K and
self field. At 4.2 K and 10 T, the $J_c$ is almost 80 kA/cm$^2$ for $B \perp$ tape plane. These results are very promising for many commercial applications. For example, transmission cables at 64 - 77 K and low field (< 0.1 T), transformers at 50 - 77 K and moderate field (0.1 - 0.3 T), and large motors at 20 - 30 K and high field (> 1 T).

B. Connectivity and Effective Flux Pinning Improvements

To reduce weak links, the c-axis texture of the Bi-2223 polycrystals must be improved. The degree of c-axis texture of these Bi-2223 polycrystals can be described by their mean misorientation angle. An estimate for this misorientation angle ($\phi$) can be made using two different techniques. In the first method, the values of $B \parallel$ tape plane and $B \perp$ tape plane at 75 K (obtained in Fig. 2a and 2b) are rescaled by $\sin(\phi)$ and $\cos(\phi)$, respectively, to characterize the average c-axis component along the non-perfectly textured grains. The $\phi$ value is chosen to collapse the $I_c$ curves for the $B \parallel$ and $B \perp$ orientations onto each other, as seen in Fig. 3. In this manner, we obtain a misorientation angle of about 7° for the 85 filament sample with self-field $J_c$ of 55 kA/cm$^2$. In the second method, the $I_c$ of the same sample is measured as a function of the angle $\theta$ between the magnetic field and the tape plane by physically rotating the sample in a constant amplitude magnetic field of 0.3 T and 75 K [14]. The $I_c$ data are plotted as a function of $B \perp$ tape plane. The misorientation angle is determined as the angle at which the $I_c - 0.3T\sin(\theta)$ curve deviates significantly from the previous two data sets, as shown in Fig. 3. This procedure yields a misorientation angle of about 8°, in good agreement with that obtained with the first method. For pressed monofilamentary samples with $J_c$ in the range of 10 - 20 kA/cm$^2$ (77 K, self field), several groups [7], [13], [16] have reported typical $\phi$ values in the range of 9 - 12° determined by both x-ray rocking curve and $J_c$ - magnetic field angular dependence techniques. There is no obvious relationship between $J_c$ and $\phi$ values for these pressed monofilament samples. However, Kobayashi et al. [17] clearly showed that the $J_c$ values for multifilamentary tapes increase from 15 to 33 kA/cm$^2$ as $\phi$ decreases from 11 to 8°. The $\phi$ value of their sample with a $J_c$ of 33 kA/cm$^2$ (8°) is similar to our sample with a $J_c$ of 55 kA/cm$^2$. This indicates that the degree of texture is not the only reason for obtaining a smaller fraction of weak links.

Fig. 4 shows the magnetic field dependence of $I_c$ for two rolled multifilamentary samples whose self field $J_c$ differs by a factor of two (22.5 to 45 kA/cm$^2$). These two samples have the same oxide core cross-section area and total conductor cross-section area, and thus, the relationship between their $I_c$ corresponds directly to that for the $J_c$. Using a technique similar to the one described above for determining $\phi$, the $B \parallel$ tape plane data have been scaled by the appropriate factor $\sin(\phi)$, where $\phi = 8.5°$, which collapses that data onto the $I_c$ data for $B \perp$ tape plane. The scaling factor also characterizes the average misorientation of the Bi-2223 platelets to the rolling direction [7],[14]. The $\phi$ values are found to be about 8.5° for both samples. This is clear evidence that the degree of c-axis texture is not the only factor that affects weak links reduction, and hence, $J_c$ performance. For the high $J_c$ sample, it appears that modifications to the processing have substantially reduced the number of weak links, either by cleaning the grain boundaries or by otherwise better connecting the grains. In either case, the useful cross-section carrying currents has increased.

We have also improved the current carrying capability in magnetic field in our composites. At 64 K, the $I_c$ magnetic field retention of three rolled 85 filament tapes with 77 K self field $J_c$ values varying from 22.5 to 45 kA/cm$^2$ is shown in Fig. 5. These samples have the same oxide core cross-section

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**Fig. 3.** $I_c$ as a function of magnetic field angle in 0.3 T plotted against $B \sin(\theta)$ and of the two principal magnetic field orientations rescaled for 7° angle for the rolled 85 filament sample at 75 K, showing degree of texture via misorientation angle estimations.

**Fig. 4.** The dependence of $I_c$ on magnetic field for two 85 filament s for the two principal field orientations at 77 K. showing weak link reduction. The $B \parallel$ field magnitude has been scaled by $\sin(8.5°)$ to account for the fitted misorientation of the grains.
current density is believed to be due mostly to reducing weak link phenomena can be decoupled, so that improvements in flux pinning and reductions in weak links in Bi-2223 composites can be separately engineered to a much greater extent than was previously believed.

Both high temperature, low magnetic field and low temperature, high magnetic field performance levels are reaching those required to impact cable, transformer, and motor applications.

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