The low-temperature, high-magnetic-field critical current characteristics of Zr-added (Gd, Y)Ba$_2$Cu$_3$O$_x$ superconducting tapes

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Abstract

Critical current performances of state-of-the-art Zr-added (Gd, Y)Ba$_2$Cu$_3$O tapes have been investigated over a temperature range of 20–77 K, in magnetic fields up to 9 T and over a wide angular range of magnetic field orientations. The peak in critical current that is commonly observed in the field orientation perpendicular to the tape in BaZrO$_3$ (BZO) containing superconducting tapes is found to vanish at 30 K in magnetic fields at 1–9 T. While the critical current of 15% Zr-added tapes was about 40% lower than that of 7.5% Zr-added tapes at 77 K, the pinning force values of the former were found to be 18–23% higher than those of the latter in the temperature range of 20–40 K and in magnetic fields of 3–5 T. The results from this study emphasize the importance of optimization of coated conductor fabrication processes for optimum performance not just in low magnetic fields at 77 K but also at the operating conditions of low temperatures and high magnetic fields that are of interest, especially for rotating superconducting machinery applications.

(Some figures may appear in colour only in the online journal)

1. Introduction

Over the last few years, extensive research has been conducted on BaZrO$_3$ (BZO) additions to thin film REBa$_2$Cu$_3$O$_x$ ((REBCO), RE = rare earth) superconducting tapes. Superior flux pinning properties have been demonstrated by BZO-incorporated REBCO thin films made by a variety of techniques including pulsed laser deposition (PLD) [1–4], metal organic chemical vapor deposition (MOCVD) [5, 6] and metal organic deposition (MOD) [7]. Unlike in PLD and MOD, BZO is formed in MOCVD thin films by addition of Zr in the metal organic precursor. Most researchers have reported the critical current properties of BZO-added thin film REBCO tapes at 77 K in magnetic fields of 1–3 T. There have been limited reports of critical current properties of REBCO tapes in high magnetic fields up to 30 T at 4.2 K [8]. However, there is a dearth of information on critical current characteristics of REBCO tapes in intermediate temperatures of 20–50 K in practical useful magnetic fields of a few tesla. It is indeed in this temperature and field range where a number of HTS applications such as wind generators, utility generators, marine and industrial motors are being developed [9, 10]. Hence, it is important that the critical current characteristics of state-of-the-art, strong flux pinning REBCO tapes are investigated in this temperature and field regime. Additionally, it has been shown that the critical current behavior in magnetic fields of 1–3 T at 77 K in BZO-added REBCO tapes is very sensitive to the
Figure 1. Magnetic field dependence of critical current of 7.5% Zr-added (Gd, Y)BCO superconducting tapes over a temperature range of 20–65 K and fields up to 9 T applied parallel to the tape surface ($B \parallel a-b$).

Figure 2. Magnetic field dependence of critical current of 7.5% Zr-added (Gd, Y)BCO superconducting tapes over a temperature range of 20–65 K and fields up to 9 T applied perpendicular to the tape surface ($B \parallel c$).

superconducting film composition and process conditions. It is not known if the film composition and deposition process optimized for 77 K, 1–3 T performance would be the optimum in the more practical relevant temperature range of 20–50 K and magnetic fields of a few tesla. This need was the motivation for this work on investigation of critical current properties of state-of-the-art Zr-added REBCO tapes over a temperature range of 20–77 K and magnetic fields of up to 9 T. Additionally, we report the influence of higher levels of Zr addition on the low-temperature, high-field critical current of REBCO tapes.

2. Experimental details

All (Gd, Y)BaCuO films made in this work were deposited in a reel-to-reel continuous MOCVD process [11]. Hastelloy C-276 substrates, 50 µm in thickness and 12 mm in width with a multilayer oxide buffer architecture were used. Biaxial texture that is essential for high critical current densities was achieved in an intermediate MgO layer using ion beam assisted deposition (IBAD) [12]. The superconducting films were grown atop a LaMnO$_3$ layer that was grown epitaxially on the MgO [13]. Previously, we had found that 7.5 at.% Zr addition yielded the best in-field critical current density at 77 K [5]. REBCO tapes with this level of Zr addition were successfully scaled up to long lengths [14, 15] and are now routinely manufactured in volume by SuperPower. We also fabricated (Gd, Y)BaCuO films with 15 at.% Zr addition in this work. Our previous results had shown inferior critical current at 77 K in samples with 15% Zr addition [5].

Transport critical current measurements were conducted at 77 K, in zero applied magnetic field and in presence of magnetic fields up to 9 T at temperatures of 20, 30, 40, 50, 65 and 77 K using a standard four probe method. The in-field critical current measurement was performed with the orientation of magnetic field parallel as well as perpendicular to the film normal. Additionally, the angular dependence of critical current was measured over an angular range of 195° to the tape axis at various magnetic fields and temperatures.

Measurements were conducted over a bridge of 1–2 mm in width because of high critical current values at low temperatures. Plan-view transmission electron microscopy (TEM) examination of a few samples were conducted to examine the morphology, orientation and size of nanoscale defects created in the films.

3. Results and discussion

The critical currents of a (Gd, Y)BCO tape with 7.5% Zr addition in magnetic fields of 0–9 T applied parallel to the tape surface ($B \parallel a-b$) over a temperature range of 20–65 K are shown in figure 1. The zero-field critical current of the tape was 475 A over a tape width of 12 mm. It is seen that critical currents reach as high as 2700 A/12 mm at 30 K, 2.5 T in this favorable field orientation, which is a factor of 5.7 higher than the 77 K, zero-field value. Also, a critical current value of 2650 A/12 mm was measured at 20 K in a magnetic field of 9 T.

As expected, the lift in critical current at low temperatures when the magnetic field was applied perpendicular to the tape surface ($B \parallel c$) was not as high. Results from measurements in this field orientation are shown in figure 2. A critical current of 1250 A/12 mm was measured at 30 K and 2.5 T in this field orientation, which corresponds to a lift factor in critical current (defined as ratio of critical current at a given temperature and field to the critical current value at 77 K, zero-field) of 2.63. This lift factor value is about two times higher than that measured in REBCO films without Zr addition.

Critical current measurements in only two magnetic field orientations do not provide the complete information needed for a coil or magnet designer since the magnetic field distribution in a coil is present over a range of orientations with respect to the HTS tape. Furthermore, critical current measurements at 77 K in low magnetic fields typically reveal a sharp minimum in the critical current at a field orientation of 15°–30° away from the $a-b$ plane. This feature can be
seen in figure 3 which displays the angular dependence of critical current of the Zr-added REBCO tape at 77 K, 1 T. It can be observed from the figure that a maximum in critical current occurs in the orientation of field normal to the tape (B $\parallel$ c) which is due to pinning by BZO nanocolumns aligned primarily along the c-axis.

Figure 4 displays angular dependence of critical current of the 7.5% Zr-added (Gd, Y)BCO tape on (Gd, Y)BCO superconducting tapes without and with 7.5% Zr addition over a temperature range of 20–77 K. All previous work on MOCVD REBCO tapes has been focused on 7.5% Zr addition because of its optimum critical current performance at 77 K, 1 T [5]. Our earlier work had shown significantly suppressed critical current in 15% Zr-added REBCO tapes at 77 K, 1 T [5]. In this effort, we
revisited the higher Zr content samples with an objective to determine if the critical current trends persisted at lower temperatures. Figure 7 exhibits plan-view microstructure of 7.5% Zr-added and 15% Zr-added (Gd, Y)BCO tape obtained using transmission electron microscopy. A high-resolution image of the microstructure of the 15% Zr-added tape is also included in the figure. Since the BZO nanocolumns are primarily oriented along the c-axis of the Zr-added samples, they appear as circular nanodefects in plan-view TEM. It can be observed from figure 7 that the spacing of the BZO nanocolumns is about 35 nm and 18 nm in the 7.5% Zr-added and 15% Zr-added samples respectively. From the high-resolution image, the diameter of the BZO nanocolumns in the 15% Zr-added sample is found to be about 4 nm, which is similar to that in the 7.5% Zr-added sample. Clearly, the density BZO nanocolumns of the 15% Zr-added samples has been increased significantly without coarsening. It could then be expected that the higher defect density would be favorable for improved flux pinning.

Figure 8 exhibits the angular dependence of critical current of (Gd, Y)BCO tapes with 7.5% and 15% Zr addition, in a magnetic field of 3 T at 20, 30, 40 and 50 and in a field of 1 T at 77 K. The zero-field critical current of the 7.5% and 15% Zr-added tapes at 77 K were measured to be 382 A/12 mm and 225 A/12 mm respectively. As mentioned earlier, it can be seen from figure 8 that the critical current of the 15% Zr-added tape is significantly inferior to that of the 7.5% Zr-added tape at 77 K, 1 T, especially in the orientation of $B \parallel c$. The prominent broad peak in critical current over a wide angular range centered around $B \parallel c$ in the 7.5% Zr-added sample is essentially non-existent in the 15% Zr-added sample. The difference in critical current between the two samples is seen to be reduced at 65 K and 3 T. The most interesting find is that at temperatures of 40 K and below, 15% Zr-added film shows higher absolute critical than 7.5% Zr-added film in spite of its substantially lower 77 K, zero-field critical current. It appears that either the higher density of BZO nanodefects or other defects in the 15% Zr-added film are becoming more active and prominent at lower temperatures resulting in improved performance. The cross over in the performance of 15% Zr-added film at lower temperatures is even more stunning when the critical current values of the two samples are normalized to their respective 77 K, zero-field values as shown in figure 9. The figure reveals that at temperatures of 50 K and below, the lift factor in critical current is significantly higher in the 15% Zr-added film over the entire range of magnetic field orientations. This finding clearly emphasizes the importance of critical current measurements in the operating conditions of interest to application of HTS coated conductors since their performance at 77 K in low fields do not properly represent their capability at lower temperatures and higher magnetic fields.

The differences in the flux pinning characteristics of the 7.5% and 15% Zr-added films over a range of magnetic fields up to 9 T applied perpendicular to the tape is elucidated in the pinning force curves shown in figure 10. It is seen from...
Figure 8. Comparison of angular dependence of critical current of (Gd, Y)BCO superconducting tapes with 7.5% and 15% Zr addition in a magnetic field of 3 T applied at 20, 30, 40, 50 K and a magnetic field of 1 T applied at 77 K.

Figure 9. Comparison of angular dependence of normalized critical current of (Gd, Y)BCO superconducting tapes with 7.5% and 15% Zr addition in a magnetic field of 3 T applied at 20, 30, 40, 50 K and a magnetic field of 1 T applied at 77 K.

figure 10(a) that the pinning force values of the 15% Zr-added film is significantly superior to that of the 7.5% Zr-added film at all temperatures at and below 40 K. The difference in the pinning force values become more substantial with reduced temperature. The improved pinning force in the 15% Zr-added film is delineated in figure 10(b) where the ratio of the pinning force values of the two samples are shown at 20, 30 and 40 K. It is evident from this figure that the 15% Zr-added film exhibits a higher pinning force at all fields above 1 T. It is also seen that the maximum pinning force improvement is in the magnetic field range 3 and 5 T at all temperatures. This result is fortuitous since several rotating machinery applications of HTS which are targeted at these temperatures involve magnetic fields in this range. It is reminded that the in-field critical current of 15% Zr-added tapes is superior at the lower temperatures in spite of their inferior performance at 77 K. If at all the zero-field critical current of the higher Zr-added films could be improved at 77 K, then even higher critical currents could be expected at lower temperatures. Indeed, we have found this to be the case [16].
Figure 10. (a) Pinning force characteristics of (Gd, Y)BCO superconducting tapes with 7.5% and 15% Zr addition at 20, 30 and 40 K in magnetic fields up to 9 T applied perpendicular to the tape ($B \parallel c$). (b) Ratio of the pinning forces of (Gd, Y)BCO superconducting tapes with 15% and 7.5% Zr addition at 20, 30 and 40 K in magnetic fields up to 9 T applied perpendicular to the tape.

4. Summary

Low-temperature, high-magnetic-field measurements of critical current of state-of-the-art Zr-added (Gd, Y)BCO tapes have been conducted in this work. The critical current at 30 K and 2.5 T applied perpendicular to the tape was found to be 2.63 times the value of critical current at 77 K, zero-field. This lift factor value is about two times higher than that measured in REBCO films without Zr addition. It was found that the peak in critical current in the orientation of $B \parallel c$ that is ubiquitously seen in HTS tapes with BZO nanocolumns essentially vanishes at lower temperatures, particularly at 30 K. The peak in the critical current in the orientation of $B \parallel a$–$b$ remains sharp till 40 K, but then broadens considerably at lower temperatures. It is also observed that the Zr-added tapes exhibit a much broader peak at $B \parallel a$–$b$ than the undoped tapes. The spacing of BZO nanocolumns was decreased from 35 to 18 nm by doubling the Zr addition from 7.5% Zr to 15% Zr, but it was found that the critical current of the 15% Zr-added tape is significantly inferior to that of the 7.5% Zr-added tape at 77 K, 1 T, especially in the orientation of $B \parallel c$. However, at temperatures of 40 K and below, 15% Zr-added film shows higher absolute critical than 7.5% Zr-added film in spite of its lower 77 K, zero-field critical current. The 15% Zr-added film exhibits a higher pinning force at all fields above 1 T. It is also seen that the maximum pinning force improvement occurs in between 3 and 5 T at 20, 30 and 40 K.

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References


[16] Selvamanickam V et al Enhanced critical currents in high levels of Zr-added (Gd,Y)BaCuO tapes *Supercond. Sci. Technol.* submitted