The use of the in-field critical current density, $J_c(0.1\,\mathrm{T})$, as a better descriptor of $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_x/\mathrm{Ag}$ tape performance

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Extended voltage–current characteristics of 13 optimized $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_x/\mathrm{Ag}$ multifilamentary tapes from four different manufacturers were extensively evaluated so as to extract the field-dependent $J_c(H)$, the characteristic field H_p obtained from the relation $J_c \sim \exp(-H/H_p)$, and the irreversibility field H^*. Values of the self-field critical current density $J_c(0\,\mathrm{T}, 77\,\mathrm{K})$ ranged from 12 to 63 kA/cm^2, $I_c(0\,\mathrm{T}, 77\,\mathrm{K})$ from 11 to 139 A, H_p from 128 to 204 mT, and H^* from 163 to 369 mT, this range thus being representative of present optimized composites. Self-field can strongly dominate $J_c(H)$ in fields below 20 mT; thus, $J_c(0\,\mathrm{T}, 77\,\mathrm{K})$ is a flawed parameter for characterizing tapes because of its very heavy dependence on self-field. We propose that a much better descriptor of tape performance is $J_c(0.1\,\mathrm{T}, 77\,\mathrm{K})$, because it lies outside the self-field and weak-link-destruction regimes and clearly within the flux-pinning-controlled domain where the connectivity-determined active cross-section carrying current is constant. [S0003-6951(99)02546-2]

Much work has been done in recent years to increase the critical current density of multifilamentary $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_x$(Bi-2223)/Ag tapes.[1–5] The normally chosen characteristic parameter is the zero applied field 77 K critical current density, $J_c(0, 77\,\mathrm{K})$, and the largest reproducible values reported so far are in the 70 kA/cm^2 range.[6] In order to continue to increase J_c it is necessary to understand and to minimize the effects of the multiple current-limiting mechanisms that operate in different field ranges for these tapes, for it is now understood that the mechanisms that limit J_c in self-field may not be the same as those which limit J_c in a magnetic field.[7] $J_c(0)$ primarily depends on the connectivity of the tape, and, in addition, it is becoming increasingly clear that self-fields can significantly suppress $J_c(0)$, especially in tapes with large critical currents.[8,9] In low fields, $J_c(H)$ is also controlled by the breaking of weak links by the magnetic field, which thereby reduces the effective cross section of the superconductor. This emphasizes that the key factor controlling the magnitude of J_c (which is almost universally defined as I_c/A, where A is the whole 2223 cross section) is the generally unknown cross section actually carrying transport supercurrent. Recently, Reimann *et al.* have shown that $J_c(H)$ can be divided into two regimes: the self-field regime at low fields where J_c is roughly constant, and a scaling regime at fields high enough so that all weak links are broken and the remaining current-carrying cross section is constant.[10] In the scaling regime $J_c(H)$ was the same for all tapes to within a proportionality constant. $J_c(H)$ is controlled by flux pinning, the strength of which can be characterized by the irreversibility field H^*. Anderson *et al.* have recently shown that there is no universal correlation between $J_c(0)$ and H^*,[11] thus suggesting that $J_c(0)$ and H^* can be optimized independently[7] and that a useful description of 2223 tape performance must include both parameters, $J_c(0)$ and H^*. In this work, we show that more extensive electromagnetic characterizations of 2223 tapes can indeed yield additional vital information about their performance and current-limiting mechanisms.

We performed an electromagnetic evaluation of 13 fully processed multifilamentary (Bi, Pb)2223/Ag tapes obtained from four different sources. The number of filaments in the tapes ranged from 8 to 55. Measurements of voltage and current were made with a standard four-terminal arrangement in liquid nitrogen in a 1 T electromagnet. The applied magnetic field was perpendicular to the tape surface, making H nominally parallel to the c axis. Voltage was measured with a Keithley 1801 nanovolt preamplifier feeding a Keithley 2001 multimeter, which produced a typical noise floor of 10 nV. V–I curves were obtained at magnetic fields from zero to as high as 600 mT, generally in steps of 10 mT up to 60 mT and in steps of 20 mT above 60 mT. H^* was found by examining the V–I curves and determining the field at which the curvature changed from positive to negative.[12,13] $I_c(H)$ was extracted from the V–I curves using a criterion of 1 μV/cm. $J_c(H)$ is defined in this letter as I_c/A, where A is the average of two or three (Bi, Pb)2223 cross sections.

$I_c(H)$ curves for two representative tapes of widely differing self-field I_c are shown in Fig. 1. [$I_c(H)$ is plotted here rather than $J_c(H)$, because it is the *current* and not the current *density* that primarily determines the size of self-field effects.) Each curve exhibits four regions. At the very lowest fields, the curves flatten because of the self-field effects, as is seen in the log–log plot in the inset. Note that $I_c(H)$ for the higher I_c tape A [$I_c(0) = 75\,\mathrm{A}$] is flattened over a much larger region, extending up to approximately 10 mT, than the curve for the lower I_c tape L ($I_c(0) = 16.7\,\mathrm{A}$. In the inset it is also seen that J_c exhibits a power-law dependence, $J_c \sim H^{-\alpha}$ (where $-\alpha$ is the slope of the linear portion of the curves on the log–log plot) from 10 mT to approximately 60 mT. Consistent with the larger role of self-field in the higher I_c composites, the quality of this fit decreases with increas-

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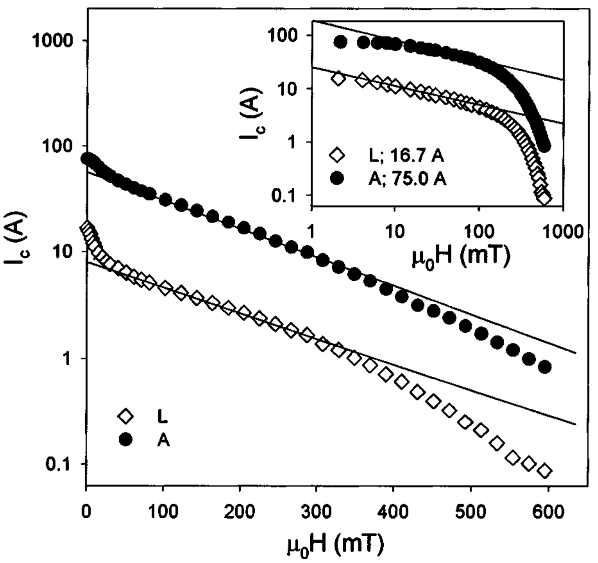

FIG. 1. $I_c(H)$ on a semilog and log–log (inset) plot for two tapes with distinctly different critical currents: tape L, $I_c(0) = 16.7$ A; tape A, $I_c(0) = 75.0$ A. The straight lines are fits to the linear portions of the curves. $I_c(H)$ of tape A is flattened by self-field effects below 10 mT; of tape L, only below ~3 mT.

ing I_c. The main graph shows that the curves have an exponential form, $J_c \sim \exp(-H/H_p)$ from 60 mT to approximately 300 mT; in this region, $J_c(H)$ is controlled by the strength of flux pinning.[14,15] Finally, above approximately 300 mT, $J_c(H)$ falls off rapidly because the irreversibility field H^* is exceeded.

Figure 2(a) shows plots of $J_c(H)$ for all the tapes in the sample set. There is a large range in $J_c(0)$ values, from 12 to 63 kA/cm^2. $J_c(H)$ also differs from tape to tape, stronger flux-pinning tapes having a smaller rate of decrease of J_c with H. In agreement with the results of Anderson *et al.*,[11] there is no direct correlation between $J_c(0)$ and in-field performance, here parametrized by H_p; for example, the tape with the highest $J_c(0)$ value of 63 kA/cm^2 (tape B), is not the same as the tape with the least slope of $J_c(H)$ (and, hence, the largest value of H_p), (tape I). To isolate the in-field performance, we normalized the $J_c(H)$ curves to $J_c(0.1\,\mathrm{T})$; the resulting plots are shown in Fig. 2(b) and their rank order in Table I. The range of in-field performance is now clearly identifiable and also clearly associated with H_p. Tapes K and I have the largest values of H_p, 204 and 202 mT, respectively, and the best in-field performance; likewise, tapes E, D, and B have the smallest values of H_p, 128, 134, and 136 mT, respectively, and the fastest drop-off rates.

Contrary to earlier work,[11] we here propose H_p rather than H^* to parametrize in-field performance, because the exponential decay of $J_c(H)$ can be evaluated at the experimentally easily accessible 1 μV/cm criterion. Table I indicates a strong, though not yet universal, correlation between H_p and H^*: for example, tape B has the lowest value of H_p (136 mT) and the lowest value of H^* (163 mT), and tape K has the highest value of H_p (204 mT) and one of the higher values of H^* (328 mT). H^* is always somewhat larger than H_p, varying from 113% of H_p (tape M) to 209% of H_p (tape C). We expect that both H^* and H_p are dependent on the flux-pinning strength. Whereas H^* is valuable because it is independent of the I_c criterion (1 μV/cm), H_p has the advantage that it depends on measurement at a higher electric-field level than does H^* and is, therefore, less sensitive to noise and to tape damage.

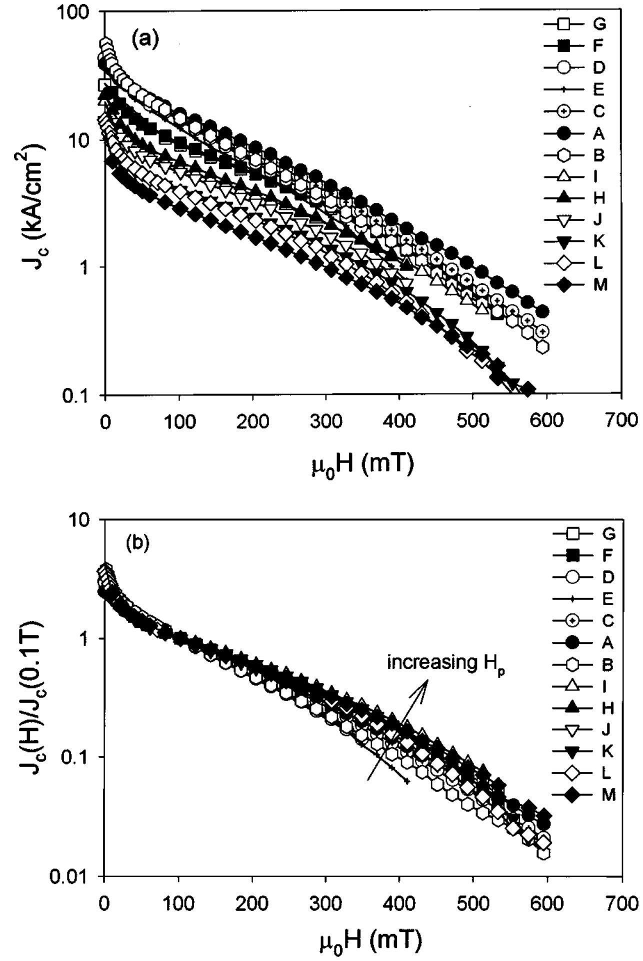

FIG. 2. (a) $J_c(H)$ for all the tapes in the sample set; (b) $J_c(H)/J_c(0.1\,\mathrm{T})$ for all the tapes in the sample set.

In Fig. 3 we focus on the behavior below 100 mT of the normalized $J_c(H)$ curves, this time on a linear plot. The low-field behavior of J_c is complicated in the region of crossover from exponential to power-law dependence. However, we note that all curves have similar shapes down to ~10 mT, consistent with the relatively small range of values

TABLE I. Tape details and summary of superconducting characterization parameters sorted by magnitude of $J_c(0.1\,\mathrm{T})$.

Tape	No. of filaments, Dimensions (mm)	$I_c(0)$ (A)	$J_c(0)$ (kA/cm^2)	$J_c(0.1\,\mathrm{T})$ (kA/cm^2)	H_p (mT)	H^* (mT)	α
A	55, 3.2×0.17	75.0	39.0	15.8	167	246	0.37
B	8, 1.9×0.09	11.1	63.1	14.7	136	163	0.35
C	55, 4.3×0.21	139.0	43.1	14.5	157	328	NA
D	19, 1.9×0.10	24.9	50.4	14.2	134	266	0.44
E	19, 1.9×0.10	20.8	47.0	12.2	128	215	0.47
F	55, 3.7×0.27	72.3	27.6	9.5	177	349	0.40
G	55, 3.7×0.27	70.0	26.7	9.1	182	369	NA
H	37, 4.7×0.22	57	22.2	6.7	188	348	0.41
I	37, 4.8×0.22	47.5	20.1	6.0	202	307	0.36
J	37, 4.8×0.21	46.6	20.1	5.6	182	225	0.37
K	37, 4.2×0.22	31.7	14.3	4.0	204	328	0.36
L	19, 3.0×0.20	16.7	14.4	3.9	186	297	0.35
M	37, 3.2×0.18	13.5	12.0	2.9	189	215	0.33

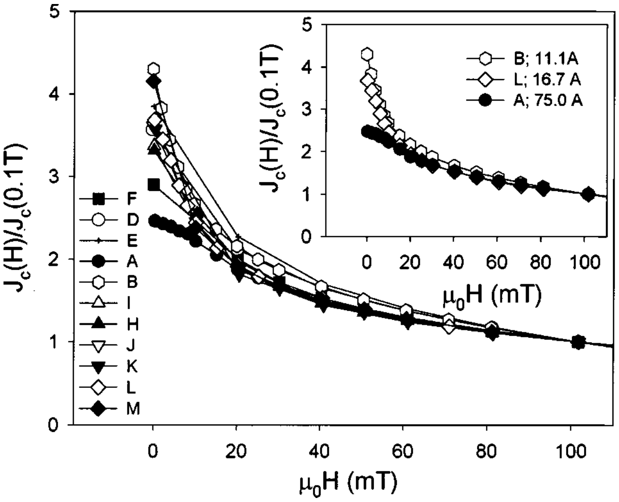

FIG. 3. Low-field behavior of $J_c(H)/J_c(0.1\,\mathrm{T})$ for all the tapes having in-field data below 60 mT. The divergence of the curves below approximately 10 mT is due primarily to self-field effects (inset); $I_c(0)$ of tape B is 11.1 A; of tape L, 16.7 A; and of tape A, 75.0 A.

of both H_p (128–204 mT) and α (0.33–0.47). This similarity makes the sudden divergence of the curves below 10 mT, where the self-field becomes the dominant current-limiting mechanism, very striking. The divergence can be roughly quantified by a comparison at different fields of values of $J_c(H)/J_c(0.1\,\mathrm{T})$. At 20 mT (where we have data points for all the samples in the plot), the spread between maximum and minimum values of $J_c(H)/J_c(0.1\,\mathrm{T})$ is 1.25, or 25% of the minimum, whereas at zero applied field, the spread is 1.75, or 75% of the minimum, three times as large. The inset to Fig. 3 shows normalized $J_c(H)$ curves for three tapes with widely different $I_c(0)$ values (11.1–75 A). It is clear that the larger the self-field I_c, the larger is the self-field suppression of $J_c(H)$, thereby making $J_c(0)$ an unreliable parameter to describe the quality of the superconductor. Figure 4 plots the ratio $J_c(0)/J_c(0.1\,\mathrm{T})$ vs $I_c(0)$ for all tapes. We note that, roughly speaking, as $I_c(0)$ increases, $J_c(0)/J_c(0.1\,\mathrm{T})$ decreases, consistent with $I_c(0)$ being the dominant factor determining self-field effects.

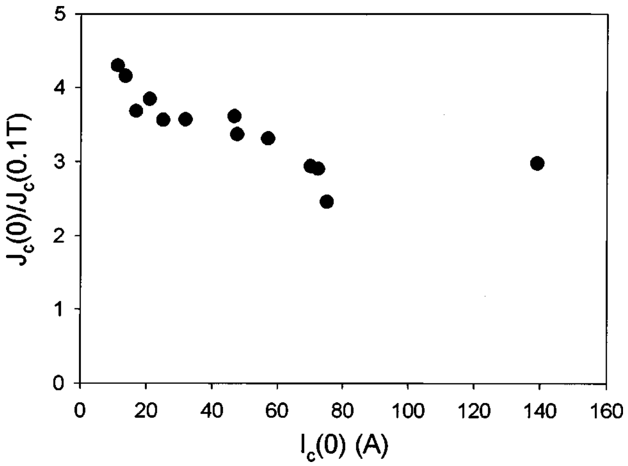

FIG. 4. Cross correlation of $J_c(0)/J_c(0.1\,\mathrm{T})$ with $I_c(0)$ for all the tapes in the sample set. Generally, the larger the $I_c(0)$ value, the greater the suppression of J_c at low fields, and the smaller the ratio $J_c(0)/J_c(0.1\,\mathrm{T})$.

In conclusion, we find that normalizing $J_c(H)$ to $J_c(0.1\,\mathrm{T})$ allows us to separate the effects of an unknown and field-varying active cross section, which limits the magnitude of $J_c(H)$, from the independent effects of flux pinning, which control the rate of drop-off of $J_c(H)$. At low fields (<10 mT), self-field effects dominate, and are very large for tapes with large self-field I_c values. Since, as we have shown, it is possible to increase $J_c(0)$ simply by reducing the 2223 cross section, thereby reducing the self-field suppression, $J_c(0.1\,\mathrm{T})$ is a better parameter to gauge tape performance than is $J_c(0)$.

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