Offset criterion for determining superconductor critical current

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(Received 23 May 1989; accepted for publication 22 June 1989)

Critical-current criteria based on electric field or resistivity can present a number of problems in defining critical current, especially for high T_c superconductors in the vicinity of the critical temperature or upper critical field. The resulting critical-current density J_c can be quite arbitrary, since it depends strongly on criterion level at high fields and temperatures. These J_c definitions also create problems in distinguishing between superconductors and high-conductivity normal metals such as copper. They can also bias J_c data when superconductors are compared that have different values of normal-state resistivity. To minimize these problems, an intrinsic J_c criterion is proposed, which effectively separates superconducting and normal-state properties. Based on the long-standing concept of a flux-flow resistivity, J_c is defined as the current where the tangent to the *E-J* curve at a given electric field level extrapolates to zero electric field. This determines an offset J_c that minimizes the above problems. The criterion is particularly useful near T_c or near the effective upper critical field where the *E-J* characteristic starts to approach ohmic behavior.

In defining the critical current of superconductors, either an electric field criterion or a resistivity criterion is generally used.[1-3] Both are illustrated in Fig. 1, which shows a schematic of electric field versus current density (*E-J*) characteristics of a superconductor at several different magnetic fields ($H1 > H2 > H3...$) approaching the upper critical field. The electric field criterion is represented by the horizontal, dashed line labeled E_c in Fig. 1. The resistivity criterion is represented by the sloped, dashed line through the origin labeled ρ_c. For both criteria, critical current is defined as the current at which the *E-J* characteristics intersect the appropriate criterion line. For high T_c superconductors, these criteria present several problems in defining critical current, especially at magnetic fields and temperatures approaching H_{c2} and T_c, where the rise in the *E-J* characteristic is gradual.

Electric field criterion. The J_c defined using these methods can depend strongly on the criterion level. For the electric field criterion, the variability in the defined J_c can be seen in Fig. 1; different values of E_c lead to relatively large changes in J_c since the rise in the *E-I* characteristic is gradual.

Another problem for the electric field criterion is that the defined J_c never reaches zero, even when the material is fully normal. This is shown, for example, by the characteristic labeled $H1$. This *E-J* characteristic has no curvature and is completely ohmic, yet the defined J_c is finite. This low residual normal-state current is usually not a problem, but when J_c is low (as at high fields) and samples are short (which prevents measurement of very low E_c), it can lead to ambiguity in the definition of superconductivity. Most measurement systems cannot detect voltages less than a few tenths of a microvolt, limiting them to electric field criteria levels greater than about $0.1\ \mu V/cm$ for short samples on the order of 1 cm in length. From the defining relation $E_c = \rho_c J_c$, it is easy to see that when J_c is below $10\ A/cm^2$, as is typical with bulk high T_c samples at fields above 0.1 T,[4] a resistivity much less than $10^{-8}\ \Omega$ cm cannot be detected by the measurement apparatus. Such a resistivity is not much lower than the low-temperature resistivity of copper.

A more subtle problem exists with the electric field criterion when comparing low J_c's at high fields near H_{c2} with greatly differing values of normal-state resistivity ρ_n, such as Tl-based high T_c superconductors versus Y-based superconductors. For a fixed E_c, the apparent J_c will be much higher in samples with a low ρ_n ($J_c = E_c/\rho_n$). Thus, when using the electric field criterion at fields approaching H_{c2}, the defined J_c for the low ρ_n materials is biased toward higher values than for the high ρ_n material.

Resistivity criterion. A number of problems also exist for the resistivity criterion. Depending on the chosen value of the resistivity criterion ρ_c (the slope of the line in Fig. 1), J_c can be made to vanish at magnetic fields spanning a considerable range. Large variability can exist, and J_c becomes arbitrary in this high-field regime.

Furthermore, in contrast to the electric field criterion (where J_c never reaches zero), J_c for the resistivity criterion can reach zero before the disappearance of all superconductivity. This is shown, for example, by the characteristic labeled $H2$ which is well beyond the resistivity criterion, but

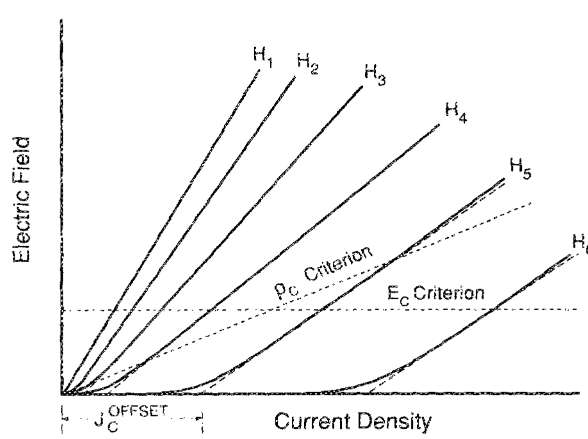

FIG. 1. Electric field vs current density curves shown schematically at high magnetic fields approaching the critical field $H1$. Electric field and resistivity criteria are shown (dotted lines), as well as the extrapolated offset J_c for each curve (the offset J_c is labeled only for curve $H5$).

 0003-6951/89/350905-03$01.00

still has curvature indicating that it is not completely ohmic.

The resistivity criterion also presents a problem in that, if the range of J_c is large, the application of the criterion is not practical. This is particularly a problem when measuring J_c as a function of magnetic field, where J_c can vary by many orders of magnitude as the field approaches H_{c2}. A high value of ρ_c must be chosen near H_{c2} where J_c is small because of the electric field detection limit of the measuring equipment discussed above. However, to maintain this high ρ_c criterion to low fields where J_c is large, the E-J characteristic must be measured to impractical levels of electric field where thermal runaway can occur.

Offset criterion. To minimize these problems, a criterion is proposed based on the long-standing concept of a flux flow resistivity. J_c is defined by taking the tangent to the E-J curve at a given electric field criterion level E_c. The critical current is defined as the current where this tangent extrapolates to zero electric field, as shown, for example, by the current marked "J_c offset" in Fig. 1.

We have used this criterion for about a year with good results in analyzing transport J_c data in a variety of Y-, Bi-, and Tl-based superconductors at magnetic fields from 10^{-4} to 10 T.[5] A typical comparison among J_c values analyzed using the three criteria is shown for a bulk sample of YBCO in Fig. 2. A value of $E_c = 10\ \mu$V/cm was chosen for taking the tangent in using the offset criterion, since this is low enough that it is comparable to typical electric field criteria, but high enough to be in the more linear region of the E-J curves near H_{c2}.

As seen in Fig. 2, the three criteria lead to nearly identical J_c values at low magnetic fields, but at high magnetic fields the differences become significant. At high magnetic fields, the offset J_c is intermediate between the J_c values determined using the two conventional criteria in Fig. 2. J_c determined using the resistivity criterion can be either very high or very low depending on the chosen value of ρ_c. J_c determined using the electric field criterion is always large, having a normal-state "tail" extending to high fields, as shown in Fig. 2. The offset J_c criterion yields a J_c less than that for the corresponding electric field criterion at the same E_c, because the normal-state tail is eliminated.

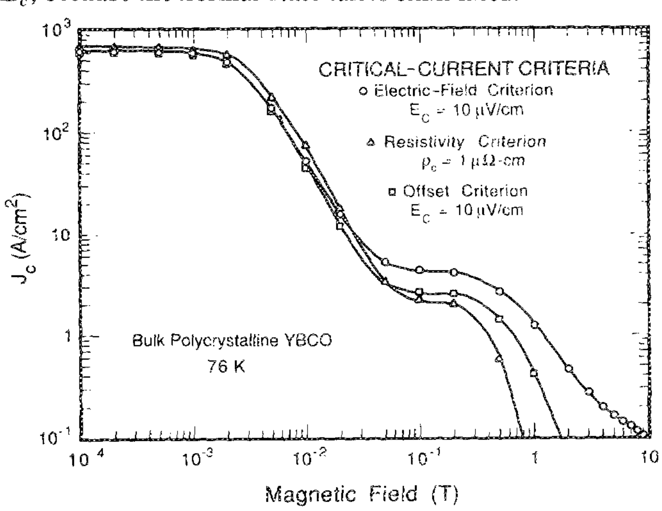

FIG. 2. Transport critical current density vs magnetic field characteristic for a bulk polycrystalline YBCO superconductor analyzed using three criteria.

Figure 3 presents the n values for the sample in Fig. 2, where n is the power-law exponent for the take-off of the E-J characteristic at the superconductor–normal transition (or equivalently, the take-off of the voltage-current or V-I characteristic). Here n is defined by $E \propto J^n$ (or equivalently, $V \propto I^n$). At low magnetic fields where the agreement between all three criteria in Fig. 2 is fairly good, n is relatively high, more than 30, as shown in Fig. 3. Near H_{c2}, differences in J_c are much more pronounced since the take-off in the E-J characteristic is very gradual, with n values less than 3.

The offset J_c can be related simply to the electric field J_c by

$$J_c^{\text{offset}} = J_c^{\text{el. field}}(1 - 1/n). \qquad (1)$$

Here the dependence of the difference between J_c^{offset} and $J_c^{\text{el.field}}$ on n can be seen explicitly.

In the high magnetic field regime, the variability of the measured J_c with the chosen criterion level is typically much less for the offset criterion than for the electric field or resistivity criteria. At very high magnetic fields or wherever the E-J curve becomes more linear after take-off, the offset J_c is nearly independent of the electric field chosen for taking the tangent, as seen in Fig. 1.

Furthermore, with such an offset J_c criterion, normal metals such as copper do not appear to have a superconducting critical current. The linear E-J characteristic of a normal metal always has an offset J_c that is zero. On the other hand, if even a small nonlinearity is present in the E-J curve, the offset J_c has a small but finite value, indicating that the material is not completely ohmic. Thus, the offset criterion is a measure of the intrinsic superconducting properties of the material and not so dependent on an arbitrary criterion level.

Finally, there is no difference in the treatment of J_c in the vicinity of H_{c2} for materials having different values of normal-state resistivity ρ_n. For the electric field or resistivity criterion, samples with low ρ_n have J_c values biased toward higher values than samples with high ρ_n, especially near H_{c2} (see Fig. 1). For the offset criterion, however, J_c approaches zero where the E-J characteristic becomes ohmic, regardless of the value of ρ_n. Thus, comparisons between different material systems having significantly different values of ρ_n, as

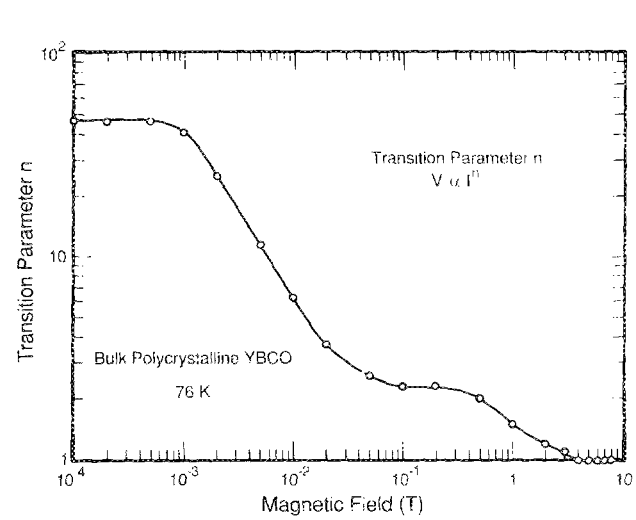

FIG. 3. Transition parameter n vs magnetic field characteristic for the same bulk high T_c superconductor as in Fig. 2.

between Tl and Y superconductors, are not biased at high fields.

A further complication with high T_c superconductors is that there can be significant flux-creep voltages at low currents, especially in single-crystal samples,[6-8] which can further interfere with the definition of J_c using a resistivity or electric field criterion.[5] Flux-creep effects, when present, result in a low-resistivity, linear E-J characteristic through the origin extending up to the nonlinear region.[6,9] The magnitude of this effect is not necessarily large but can vary greatly with intragrain defect structure and surface pinning (especially in film materials).

Fortunately, the presence of thermally activated flux creep does not interfere with the offset definition. In contrast to the low-current flux-creep voltages, the offset J_c criterion being described here is applicable to defining a *flux flow* or depinning critical current at high currents. The J_c so defined depends entirely on back extrapolation of the E-J characteristics from currents where flux-flow voltages dominate. (Alternatively, if flux-creep voltages are large enough to measure, and a low E_c is chosen to probe the low-current, linear flux-creep regime, the resulting offset J_c would be zero because of the ohmic nature of the E-J characteristic in this regime; this makes much more physical sense than an arbitrary, finite J_c that would be obtained using either an electric field or resistivity criterion.)

In the flux-flow regime there is generally a nonlinear region of the V-I curve, followed by a region that is usually more linear when vortex pinning is weak, as at high magnetic fields approaching H_{c2}. The nonlinear region leading into the linear region has been explained in terms of different mechanisms, including flux creep.[6,9,10] It can also be explained simply in terms of a variation in the local value of the depinning critical current along the length of the sample[11-15] or along percolation paths within the sample, resulting from variations in purity, crystal structure, crystal orientation, stoichiometry, or surface conditions. This is the situation especially at high fields near H_{c2} where the effects of material inhomogeneities on J_c become magnified.

The offset J_c has a simple physical interpretation in this case.[12] Assume that the sample has a normalized distribution $g(I_c)$ of locally varying critical currents along its length, with minimum and maximum critical current values $I_c^{\min}$ and $I_c^{\max}$. [The second derivative d^2V/dI^2 of the nonlinear region is directly proportional to $g(I_c)$, assuming the flux-flow resistivity of the sample is spatially constant.[11]] Above $I_c^{\max}$ the V-I characteristic will be linear. If E_c is in this linear region,[12] we obtain a very simple expression,

$$I_c^{\text{offset}} = \int_{I_c^{\min}}^{I_c^{\max}} i g(i) di.$$

That is, the offset critical current near H_{c2} (or wherever E_c is in the approximately linear region) corresponds physically to the *average* I_c of the depinning critical-current distribution $g(I_c)$ in the sample.

Thus, the offset criterion is useful for studies of intrinsic superconducting properties. It defines a superconducting J_c that goes to zero where the E-J characteristic of a material becomes completely ohmic, unlike conventional criteria where the defined J_c is the result of an arbitrary interaction between criterion level and normal-state conduction. Of course, for a specific engineering application where a voltage or resistance level can be specified (and if it does not matter whether the conduction is via superconducting or normal-state current), any of the three criteria can be used about equally well. (Most applications, though, utilize superconductors operating where they have high J_c and n, precisely the regime where the distinction between the three criteria becomes more of a moot point.) However, from a physics standpoint when studying the superconducting properties of a material, especially at high fields or temperatures, the offset criterion is preferred because the approach of J_c^{offset} to zero intrinsically defines where the E-J characteristic becomes ohmic. Essentially, the offset criterion is similar to the electric field criterion [see Eq. (1)], but it eliminates the normal-conduction component inherent to the electric field criterion, and much of the arbitrariness associated with the criterion level when J_c and n become small.

The author wishes to acknowledge stimulating discussions with J. Cave, G. A. Reinacker, S. L. Bray, L. F. Goodrich, F. R. Fickett, and R. L. Peterson. G. A. Reinacker assisted with the data analysis.

[1] J. W. Ekin, Appl. Phys. Lett. **29**, 218 (1976).
[2] A. F. Clark and J. W. Ekin, IEEE Trans. Magn. **MAG-13**, 38 (1977).
[3] Am. Soc. for Testing and Mat., Standard #B714-82, ASTM, Phil., PA.
[4] J. W. Ekin, A. I. Braginski, A. J. Panson, M. A. Janocko, D. W. Capone, II, N. J. Zaluzec, M. Flandermeyer, O. F. de Lima, M. Hong, J. Kwo, and S. H. Liou, J. Appl. Phys. **62**, 4821 (1987).
[5] J. W. Ekin, T. M. Larson, A. M. Hermann, Z. Z. Sheng, K. Togano, and H. Kumakura, Physica C (to be published).
[6] T. T. M. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, Appl. Phys. Lett. **54**, 763 (1989).
[7] M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).
[8] Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988).
[9] P. W. Anderson and Y. B. Kim, Rev. Mod. Phys. **36**, 39 (1964).
[10] P. W. Anderson, Phys. Rev. Lett. **9**, 309 (1962).
[11] R. G. Jones, E. H. Rhoderick, and A. C. Rose-Innes, Phys. Lett. A **24**, 318 (1967).
[12] J. Baixeras and G. Fournet, J. Phys. Chem. Solids **28**, 1541 (1967).
[13] J. W. Ekin, Cryogenics **27**, 603 (1987).
[14] C. J. G. Plummer and J. E. Evetts, IEEE Trans. Mag. **MAG-23**, 1179 (1987).
[15] W. H. Warnes, Adv. Cryo. Eng. **34**, 697 (1988); W. H. Warnes and D. C. Larbalestier, Cryogenics **26**, 643 (1986).