Critical currents in polycrystalline $YBa_2Cu_3O_{7-x}$: Self-field and grain-size dependence

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The variation of critical currents and their distributions with thickness has been investigated for two high-quality $YBa_2Cu_3O_{7-x}$ samples with different average grain size (10 and 30 μm for samples S_1 and S_2, respectively) in the temperature range 78–90 K and in the applied magnetic field $H<50$ Oe. The critical-current density (J_c) for S_1 initially increased but later on leveled off on reducing the thickness, whereas for S_2 remained essentially unchanged even after threefold reduction in thickness. Since the other parameters related to macroscopic homogeneity have not changed on reducing the thickness of the samples, the variations of J_c are interpreted in terms of thickness and grain-size-dependent self-field effects. The same model explains well the changes of critical-current distribution curves with thickness and may also explain the variation of J_c with the grain size, as reported recently for ceramic Y-Ba-Cu-O samples.

I. INTRODUCTION

For some time it has been recognized that, for the majority of ceramic $YBa_2Cu_3O_{7-x}$ (Y-Ba-Cu-O) samples, the critical current (I_c) is limited by its self-field.[1,2] The variation of the critical-current density (J_c) with the dimensions (cross section) of the sample provides rather direct evidence for this effect.[1–3] This led to the idea that the problem of very low J_c in polycrystalline samples of Y-Ba-Cu-O may be partially solved by preparing very thin samples, such as filaments or sheets.[3] However, it was recently shown that the self-field effects mask the intrinsic temperature and magnetic-field dependences of I_c in these samples.[4] In particular, the intrinsic H and T dependences of I_c [$\propto \exp(-H/H_0)$ and $\propto(1-T/T_c)^2$, respectively[4]] are modified by the self-field effects to the well-known Fraunhoffer diffraction-like and quasilinear or concave-upward variations. It has also been found[4] that the transport measurements of I_c reveal the intrinsic I_c value and variations only in samples with very low J_c (<20 A cm^{-2}). However, even for samples in which transport measurements yield a self-field limited I_c, the intrinsic I_c and its variations can both be determined from the high-resolution measurements of ac susceptibility in very low fields.[5]

It has been recently shown that the rather broad and featureless distributions of critical currents exist within the polycrystalline Y-Ba-Cu-O samples.[6,7] Apparently, as in conventional type-II superconductors,[8] these critical-current distributions (CCD) are associated with the microstructural characteristics (related to preparation and processing) of a given sample. Therefore, for a full assessment of the potential of high-T_c superconductors, a detailed investigation of their CCD curves is necessary. However, since a CCD curve is determined from V-I measurements at currents in excess of I_c, the self-field effects may affect the CCD curves for polycrystalline Y-Ba-Cu-O samples.[9] Therefore, the interpretation of CCD curves for ceramic samples would be more involved than for conventional type-II superconductors. In particular, for a meaningful comparison of the microstructural findings with a CCD curve of the same sample, a prior knowledge of the self-field effect on the obtained CCD curve is required.

To our knowledge no systematic study of the self-field effects on I_c and a CCD curve of ceramic Y-Ba-Cu-O samples has been performed so far. Therefore, the important questions, such as down to what dimensions these effects persist, whether the self-field effects in these samples could at all be treated as those in homogeneous superconductors, etc., remain to be answered.

In this paper we report the results of the systematic investigation of the changes in I_c and the CCD curve caused by the reduction of the thickness (t) of the well-characterized ceramic Y-Ba-Cu-O sample (S_1) with the average grain size ($d_{g,\mathrm{av}}$) of about 10 μm. It is found that a change in I_c (with t) is not quite the same as is expected for a homogeneous superconductor and that the increase of J_c with decreasing t actually ceases to exist below a certain t. In order to verify whether this behavior is related to $d_{g,\mathrm{av}}$ of a given sample, we performed similar measurements on another sample (S_2) prepared from the same reacted powder but, due to the prolonged sintering time, with larger grains ($d_{g,\mathrm{av}}\simeq 30$ μm). For this sample J_c turned out to be independent of t. The same result was also obtained for an additional sample (S_3) with

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$d_{g,av} \simeq 100$ μm. A simple explanation for the observed behaviors is provided.

II. EXPERIMENT

A starting x-ray pure material in the form of a fine superconducting powder of $YBa_2Cu_3O_{7-x}$ was prepared by the use of a standard ceramic procedure. Two batches of pellets were prepared, placed on a Pt foil in an allumina boat, and annealed at 960 °C in oxygen atmosphere for 7 (S_1) and 70 (S_2) h, respectively, then socked for 17 h at 750 °C in oxygen and slowly cooled down to the room temperature. An increase of (001) peaks intensities in an x-ray-diffraction (XRD) pattern of sample S_2 indicates the increasing size of the platelike-shaped grains with annealling time. The scanning electron microscopy (SEM) investigation showed that $d_{g,av}$ increased from approximately 10 (S_1) to 30 μm (S_2). Typical electron micrographs of the samples S_1 and S_2 are shown in Fig. 1. Simultaneously, the density of the pellets increased from 5.1 (S_1) to 5.8 g cm^{-3} (S_2). The samples for the actual measurements were cut out from the central part of the respective pellets. The initial dimensions of the samples were $11\times1.8\times0.75$ mm^3 and $12\times1.6\times1.6$ mm^3 for S_1 and S_2, respectively. The low-resistance contacts for the transport measurements were prepared by baking the silver paste (Demetron Leit Silber) for about 15 min at 400 °C in oxygen atmosphere onto the samples. The current and voltage leads were subsequently fixed onto this contact at room temperature by the same contacting material. The thinning of the samples was performed in such a way that the silver contacts remained intact; hence, the same contacts were used in the entire sequence of measurements. (This resulted in the platelike geometry, preferred for the determination of J_c from ac susceptibility measurements.)

The resistivity was measured with a standard ac method. The *V-I* characteristics were taken over a broad current range by the use of the single pulse method as described earlier.[6,7,9] Experiments with the pulses of different widths (0.05–5 s) showed that neither I_c nor the CCD curve depend on the pulse duration. The critical-current densities were also determined from the ac susceptibility measurements[4,5] performed at 28.4 Hz and different amplitudes (0.01–15 Oe) of ac magnetic field. These measurements were performed on the same samples shortly after the transport properties measurements. The investigations of critical currents were performed in the temperature range 79–90 K and in the applied dc magnetic fields $H<50$ Oe. Some data relevant to our samples are given in Table I.

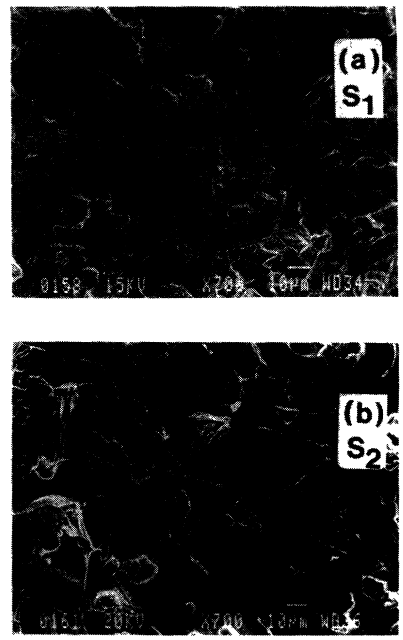

FIG. 1. SEM of $YBa_2Cu_3O_{7-x}$ (a) sample S_1 sintered for 7 h and (b) S_2 sintered for 70 h.

III. RESULTS

The data listed in Table I indicate a good quality of our samples. The resistive superconducting transition temperatures T_{c0} were high and the transition widths narrow ($\Delta T_c=1$ K and $\Delta T_c=1.1$ K for samples S_1 and S_2, respectively). Furthermore, the resistivities (ρ) were low and strongly temperature dependent. The resistivity of S_2 was remarkably low as expected for a dense sample with large grains (hence, with a relatively small number of rather large intergrain junctions). The extrapolation of the linear part of the resistivity of the sample S_2 to $T=0$ K yielded $\rho=0$.

Regarding the *V-I* characteristics of samples S_1 and S_2, the transition parameters[10] n (at 80 K and zero applied field), i.e., the initial power-law exponents of the *V-I* curves, are quite large compared to the values frequently reported for the ceramic Y-Ba-Cu-O.[6,11,12] This indicates relatively narrow critical-current distributions. Sizably larger n for S_1 than for S_2 reveals a sharper transition to a dissipative state immediately above I_c, and thus, possibly, a larger density of critical currents with the magnitudes within this current range in sample S_1. As shown in Table I, there is a rather large difference in ratio of the differential (slope) resistance[10,11] to that at 95 K

TABLE I. Data relevant to ceramic $YBa_2Cu_3O_{7-x}$ samples. D is the density, $\rho_{295\,K}$ is the resistivity at 295 K, T_{c0} is the temperature at which $\rho=0$, n is the initial exponent of the $V\propto I^n$ curve at 80 K, R_f is the differential resistance (slope of the *V-I* curve when it becomes linear), and χ' and χ'_g are the real parts of ac susceptibility in low (0.008 Oe rms) and high fields (10.5 Oe rms), respectively, at 80 K.

Sample	D (g cm^{-3})	$\rho_{295\,K}$ ($\mu\Omega$ cm)	$R_{295\,K}/R_{95\,K}$	T_{c0} (K)	n	$R_f/R_{95\,K}$	χ'	χ'_g/χ'
S_1	5.1	950	2.5	92	21	0.14	−0.92	0.73
S_2	5.8	510	3.2	91.5	14	0.04	−0.96	0.91

$(R_f/R_{95\,\mathrm{K}})$ between two samples. (R_f is the slope of a linear part of the V-I curve and in ceramic Y-Ba-Cu-O samples it reflects the dissipation in the sample whose grains are still superconducting.) This is also consistent with the difference in the grain sizes of the samples.[6] Whereas $R_f/R_{95\,\mathrm{K}}$ for S_1 is typical for the fine-grained ceramic samples,[11,5,6,9] that for S_2 is to our knowledge the lowest reported so far.

The low-field ac susceptibility measurements have shown a rather narrow diamagnetic transition for both samples (Fig. 2) and almost complete diamagnetic shielding at 80 K (Table I). The ratio of the real part of the ac susceptibility (χ') at low fields to that at the elevated field ($H_{\mathrm{ac}} \geq 10$ Oe rms, i.e., H_{ac} is sufficient to decouple the superconducting grains at 80 K) indicates that the grains accounted for about 0.7 (S_1) and 0.9 (S_2) of the total volume of the sample. About three times larger intragrain maximum of the imaginary part of ac susceptibility (χ'') at high field of the sample S_2, compared to that of S_1 (inset to Fig. 2) is also consistent with an increase in the grain size.

Most of the parameters listed in Table I did not change (within the experimental error) upon the subsequent thinning of the samples. Only a small increase of exponent n (from 13 to 15) by decreasing thickness (t) was observed for sample S_2. The insensitivity of the parameters mentioned above upon strong reduction in thickness (0.73–0.37 and 1.6–0.68 mm for samples S_1 and S_2, respectively) seems to indicate the macroscopic homogeneity of our samples as well as the absence of any larger damage due to the thinning procedure, repeated thermal cycling and prolonged measurements.

The critical currents (I_c) and the critical-current densities (J_c) determined from the V-I curves at 80 K for different thickness of the samples are shown in Fig. 3. A decrease in I_c accompanied by an increase of J_c on reducing the thickness of sample S_1 seems consistent with the measurement-current self-field (H_s) limited I_c of a homogeneous superconductor. Indeed, by the virtue of Ampere's law, the current I flowing along a sample is accompanied by the magnetic field (self-field) H_s which at its surface takes the value $H_s = I/(2w+2t)$, where w and t are the width and the thickness of the sample, respectively. Because of this, if the critical current I_c is self-field limited, it should decrease linearly on decreasing t $[I_c = H_s(2w+2t)]$ and critical-current density $J_c = I_c/wt$ should linearly increase with t^{-1}. Furthermore, from the slopes of I_c versus t and J_c versus t^{-1}, down to 0.43 mm one could (erroneously as shown below) deduce a constant $H_s \approx 12$ Oe in this range of t.

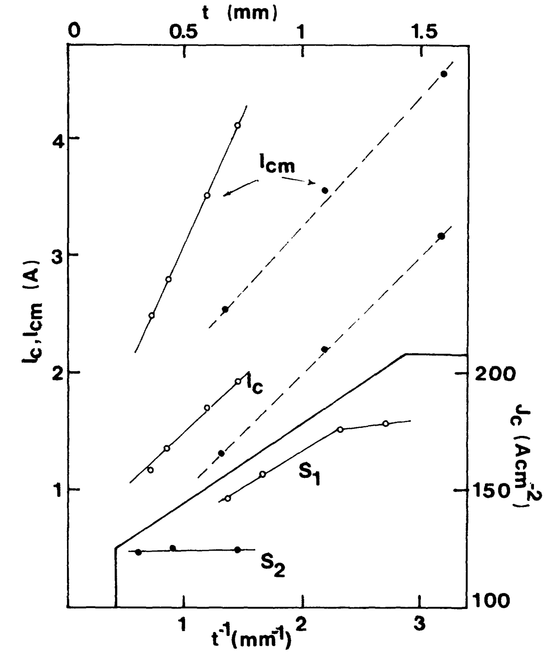

FIG. 3. Variation of critical current I_c and maximum critical current I_{cm} with thickness t, for samples S_1 (○) and S_2 (●). I_c is the current above which the dissipation sets in (according to 0.1-μV voltage criterion) and I_{cm} is the current above which the V-I curve becomes linear, i.e., critical-current distribution function reaches zero. The inset shows the dependence of the critical-current density J_c (I_c divided by the cross section wt) with t^{-1} for the same samples. The straight lines are guides for the eye only.

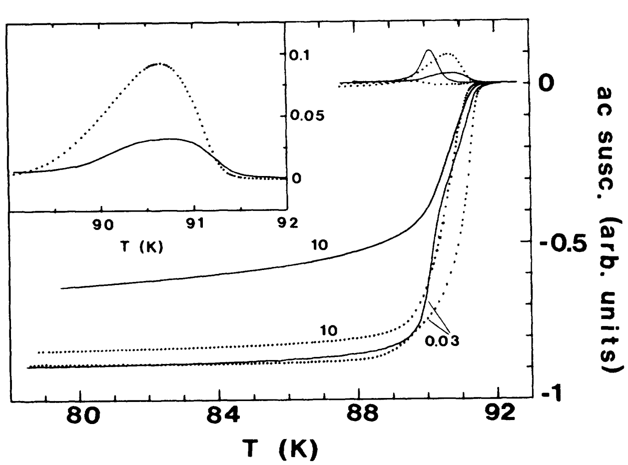

FIG. 2. ac susceptibility (real and imaginary part) of Y-Ba-Cu-O sample S_1 (solid) and S_2 (dotted) vs temperature. The numbers denote rms values of the ac field (in Oe). Inset: intragrain maxima of the imaginary part of the ac susceptibility of the same samples in 10 Oe rms ac field.

The critical-current-density data can be also deduced from the imaginary part (χ'') of the ac susceptibility. The numerous measurements of this quantity reveal the double-peak structure in corresponding temperature dependence as its universal feature. As widely accepted, the maxima correspond to either intergrain or intragrain eddy current dissipation. These maxima in χ'' can be easily identified by the measurements of their temperature position in the sequence of applied magnetic fields:[13] the intergrain maximum depends much stronger on the applied field than the intragrain one. For our samples both maxima can be easily separated and the critical-current density for the platelike geometry is $J_{c\chi''}(H_0,T) = 1.5H_0/t$. H_0 is the amplitude of the ac field for which the intergrain maximum of χ'' occurs at a given temperature T. The measured $J_{c\chi''}$ also increases approximately linearly with t^{-1} (Table II) but with a slope somewhat larger than that for transport J_c (Fig. 3). Since the full penetration of the magnetic field occurs at lower field in thinner sample, $J_{c\chi''}$ is measured in a lower field, which shows up as an increase in $J_{c\chi''}$ on decreasing t.

The effects of the applied ac field (H_0) and the self-field on the measured critical-current densities ($J_{c\chi''}$ and $J_{c''}$, respectively) have been demonstrated by measuring the "zero-field" critical-current density,[4,5] $J_{c\chi'}$, of sample S_1. $J_{c\chi'}$ is deduced[4,5] from the variation of χ' with the amplitude of the ac field H_0 for low H_0, by taking into account the contribution of the intergranular material to χ' only. The initial linear variation of χ' with H_0 yields $J_{c\chi'}(T,H\rightarrow 0)=(\alpha/t)(\Delta H_0/\Delta\chi')$, where α represents the fraction of the intergranular material. For both $t=0.43$ and 0.37 mm, the high-resolution ac susceptibility measurements yielded practically the same $J_{c\chi'}(H\rightarrow 0, 80\ \mathrm{K})\cong 300\ \mathrm{A/cm^2}$, sizably larger than $J_{c\chi''}$ and J_c (Table II).

The temperature and magnetic-field dependencies of I_c for sample S_1, shown in Fig. 4, are typical for a ceramic sample with the self-field limited critical current. It is interesting to note that the temperature dependence of $J_{c\chi''}$ is almost the same as that of J_c. This seems to indicate that the effect of an applied field (H_0) on $J_{c\chi''}$ is qualitatively the same as that of (temperature dependent) H_s on $J_c(T)$. The similarity between $J_{c\chi''}(T)$ and $J_c(T)$ seems to break close to T_c, where $J_{c\chi''}$ shows almost an intrinsic variation with T, probably because of very low H_0 in this temperature range. Within the experimental error temperature dependence of J_c does not change with t.

In contrast to that, the variation of J_c with the applied dc magnetic field becomes more pronounced on decreasing t [Fig. 4(b)]. The simplest explanation for this effect is that the self-field is not actually constant but decreases with t. [Note that $J_c(H)$ tends to saturate when H becomes smaller than H_s.] Indeed, from the experimental data for I_c (Fig. 3) and Ampere's law $H_s=I_c/(2w+2t)$, it follows that H_s decreases slowly for $t\leq 0.73$ mm and approximately linearly with t for $t\leq 0.43$ mm. The approximate linear I_c versus t dependence (whose slope tends to be interpreted as $2H_s$) shown in Fig. 3 obviously oversimplifies the actual dependence. In particular, the decreasing H_s causes a rapid variation of I_c with t (faster than the variation which would be obtained if H_s were constant) and leads to an erroneous (too high) estimation of the value for H_s (12 Oe) from the slope of the I_c versus t curve.

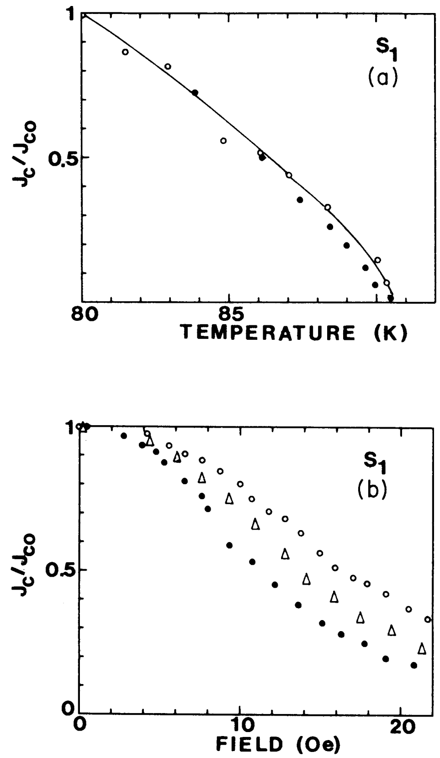

FIG. 4. (a) Variation of the critical-current density J_c normalized to its value at 80 K for sample S_1 with temperature. (○) and (●) denote J_c determined from the *V-I* curves and the imaginary part of the ac susceptibility, respectively. (b) Variation of the critical-current density J_c at 80 K normalized to its value in zero applied field vs applied magnetic field for three thicknesses of sample S_1: 0.73 (○), 0.43 (●), and 0.37 mm (△).

For a homogeneous superconductor with the self-field limited I_c, the decrease of H_s on reducing the thickness of the sample would not be expected. Since the parame-

TABLE II. Data relevant to critical currents and their distributions for sample S_1 at 80 K. $J_{c\chi'}$ and $J_{c\chi''}$ are the critical-current densities deduced from the real and imaginary parts of ac susceptibility. J_c is the critical-current density deduced from the *V-I* curve. J_{cp}, J_c', and J_{cm} are the most probable, average, and maximum critical-current density deduced from the critical-current distribution, where W_F denotes its full width.

Thickness (mm)	$J_{c\chi'}$	$J_{c\chi''}$	J_c	J_{cp} (A/cm²)	J_c'	J_{cm}	W_F/J_c'
0.73		148	147	178	190	320	1.01
0.6		168	157	192	208	330	0.86
0.43	340	219	177	215	232	350	0.82
0.37	330	226	179	224	236	360	0.84

ters listed in Table I do not indicate that the macroscopic homogeneity of S_1 changes on thinning, it seems that the description of the behavior of that sample in terms of the self-field effects in the homogeneous superconductor is not entirely appropriate. More precisely, such a description seems to become less and less justified on reducing the thickness of the sample. Indeed, a rather strong decrease of I_c on reduction of the thickness of S_1 beyond 0.43 mm resulted in a negligible increase of J_c (Fig. 3) which seems to support that viewpoint. Therefore, it seems that, below a certain thickness, the behavior of I_c of ceramic Y-Ba-Cu-O samples is not governed by the "macroscopic" self-field (the one pertaining to the sample as a whole). This shows up in a critical current which is proportional to the sample's cross-sectional area (wt) rather than to its circumference $(2w+2t)$, hence, in a constant $J_c=I_c/wt$. The actual thickness at which this crossover occurs will apparently depend on the grain size (Fig. 3) and may also depend on the actual preparation conditions (thus, on density, porosity, impurities, eventual texture, etc.). Indeed, it seems surprising that a complex percolative flow of critical current between the grains of ceramic superconductor could at all be described in terms of the self-field limited I_c of the homogeneous superconductor. However, one can visualize the appearance of such behavior as a result of the effective cancellation of the fields of the adjacent individual current filaments in the interior of the ceramic sample. In that case, the macroscopic self-field would exist mainly along the circumference of the cross section of the sample and an approximate self-field limited behavior of I_c may result. Apparently, on reducing the sample's cross section (or on increasing the grain size), such an effective cancellation becomes more difficult to achieve. (In particular, at some stage a flow of the effective self-field may not coincide with the actual circumference of the sample which may result in the faster decrease of I_c with the geometrical thickness of the sample.) Finally, when the cross section of a sample becomes sufficiently small (or the grains large enough), only a partial cancellation of the self-fields of the current filaments occurs in the interior of the sample, and the difference between the field in the interior and that at the surface of the sample vanishes. The sample behaves more or less as an assembly of the individual filaments (carrying critical currents in parallel), hence, the total I_c becomes proportional to the cross-sectional area and the critical-current density becomes a constant. The description of the critical-current behavior in terms of the macroscopic self-field becomes, in this case, obviously inappropriate. However, the variations of the total critical current with the magnetic field and temperature may still show the effects of the self-field because the critical currents of the individual filaments may also be self-field limited (depending, for instance, on J_c of the individual filament[4]). At that stage, however, the effective self-field of reasonably homogeneous sample should not change much with thickness.

The results for sample S_2 ($d_{g,\mathrm{av}}\approx 30$ μm) shown in Fig. 3 support the above explanation. Since the critical-current density remained practically the same, even after almost threefold reduction in thickness, this sample seems to behave as an assembly of individual (still self-limited) critical currents. (We note that, although the initial thickness of S_2 was 1.6 mm as compared to 0.73 for sample S_1, the difference in $d_{g,\mathrm{av}}$ of two samples (30 and 10 μm, respectively) accounts for more than the difference in the initial thicknesses). Furthermore, the magnetic field dependence of I_c for S_2, shown in Fig. 5, did not change much on thinning, indicating a roughly constant H_s.

Recent measurements of the dependence of J_c on the grain size in thin ceramic Y-Ba-Cu-O samples[14,15] are also consistent with the above description of the self-field influence on critical currents in such samples. Large values of J_c for samples with $d_{g,\mathrm{av}}\approx 1-2$ μm are probably due to the large macroscopic self-field effects in the fine-grained samples. A weakening of these effects (a decrease in H_s) is probably responsible for a rather rapid decrease of J_c on increasing $d_{g,\mathrm{av}}$. Finally, a slow (if any) variation of J_c on further increase of $d_{g,\mathrm{av}}$ (Ref. 15) is consistent with the individual conduction regime. Our preliminary results for the Y-Ba-Cu-O sample (S_3) with $d_{g,\mathrm{av}}$ of about 100 μm (prepared in the same way as S_1 and S_2 but annealed for 700 h) also lend support to the presented model. Critical-current density for that sample at 80 K (≈ 110 A/cm^2) was slightly lower than that for S_2 (Fig. 3) and again did not practically change on reducing its thickness from 1.6 to 0.9 mm. The other results for S_3 follow the trend indicated by the data for S_1 and S_2 (Table I). In particular, its resistivity, R_f and the exponent n are somewhat lower than those for S_2 (Table I), whereas the V-I curves (including I_c-H and I_c-T dependencies) indicate behavior analogous to that observed for S_2.

The effects described above should also affect the critical-current distribution curves of our samples. In particular, the variation of critical current within the sample should be associated with the variation of the self-field. For the sake of clarity, we shall briefly review the basic relations connecting the V-I and CCD curves. Baixeras and Fournet[16] have shown that the potential developed across the type-II superconductor sample is

$$V(I)=A\int_0^I (I-I')f(I')dI' \ , \qquad (1)$$

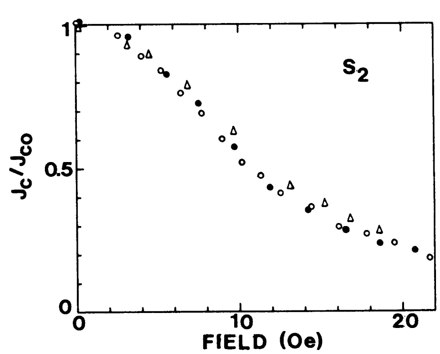

FIG. 5. Variation of the critical-current density J_c at 80 K normalized to its value in zero applied field vs applied magnetic field for three thicknesses of sample S_2: 1.6 (○), 1.1, (●), and 0.68 mm (△).

where I' is the local critical current, $f(I')$ is the normalized distribution (probability density) of the critical currents in the sample $[\int_0^\infty f(I')dI'=1]$ and A is a factor describing the dissipation processes occurring in the portions of sample where $I>I'$. Accordingly, the effective resistance of the sample at a given current is

$$R(I)=A\int_0^I f(I')dI' \ . \qquad (2)$$

At elevated currents (when the V-I curve becomes linear), $dV/dI=A$, which corresponds to a measured differential resistance, R_f. This can be used to deduce the resistive (dissipating) fraction of the sample at a given current, $F_D(I)=R(I)/R_f$. [For a ceramic sample $F_D(I)$ refers to intergrain junctions rather than to a total volume of the samples.] The CCD curve can then be obtained by differentiating $F_D(I)$ with respect to I:

$$f(I')=(1/R_f)(d^2V/dI^2) \ . \qquad (3)$$

CCD curves corresponding to the different thickness of sample S_1 ($T=80$ K, $H=0$) are shown in Fig. 6. These curves are usually characterized by three parameters:[8] the most probable (common) critical current I_{cp} (for which the curve reaches its maximum value), the highest critical current exhibited by the distribution I_{cm}, and the average critical current $\langle I_c\rangle$ $[\langle I_c\rangle=\int_0^\infty If(I)dI]$.

The extrapolation of the linear part of the V-I curve to $V=0$ yields the offset critical current[12] I_c', a parameter which is useful both for understanding the effective resistance [Eq. (2)] and the analysis of the CCD curve.[17] In particular, if the effective resistance of a sample is spatially constant, then $I_c'=\langle I_c\rangle$;[17] the inequality is a sign of the sample's nonuniformity. For the present sample (as well as for all other ceramic Y-Ba-Cu-O samples investigated by us so far[6,7,9]) I_c' appeared to be practically the same as $\langle I_c\rangle$.

Rather narrow CCD curves (Fig. 6) have allowed a quite accurate determination of the above parameters. These curves are also quite symmetrical which results in a small difference between I_c' and I_{cp} ($I_c'/I_{cp}=1.07\pm0.02$). The variations of I_c and I_{cm} are shown in Fig. 3 and the corresponding critical-current densities (J_{cp}, J_c', and J_{cm}) are listed in Table II. (We note that, as for composite superconductors with linked filaments[8] the path from the measured I_c distribution to the J_c distribution is probably quite complex and therefore the actual meaning of the values of J_{cp} and J_{cm} is less clear than that of I_{cp} and I_{cm}). The variation of I_{cm} with t (Fig. 3) is much faster than that of I_c, resulting in the strong narrowing of CCD curves on decreasing t (Fig. 6). If the effective self-fields corresponding to I_c and I_{cm} were independent of t, the full width of the CCD curve should scale with $(2w+2t)$ and its relative width $W_F/\langle I_c\rangle$ should be independent of t. However, as shown in Fig. 6, W_F of the CCD curve for S_1 changes faster than $(2w+2t)$ and accordingly $W_F/\langle I_c\rangle$ decreases with decreasing t (Table II). Therefore, it seems that the effective self-field corresponding to I_{cm} decreases more rapidly with t than H_s does. This seems plausible since, at such high currents, the effective cancellation of the self-fields of the adjacent current filaments is less likely to occur than at I_c. We note, however, that the decrease of $W_F/\langle I_c\rangle$ with t seems to end for $t<0.43$ mm, which is probably associated with the transition to the conduction by the individual current filaments.

CCD curves for different thickness of sample S_2 ($T=80$ K, $H=0$), shown in Fig. 7 give support to the above assumptions. For that sample, W_F's of CCD curves become only a little narrower on decreasing t. Such a behavior is also consistent with the concept of varying self-fields corresponding to I_c and I_{cm} and could be explained in terms of the conduction by the individual current filaments in a coarse-grained or a very thin sample. Indeed, as the thickness of a sample becomes comparable to $d_{g,\mathrm{av}}$, a redistribution of current within the sample will likely follow the further reduction of its thickness. Whatever the nature of the actual redistribution is, it should show up in the corresponding CCD curve. The comparison of CCD curves for S_2 (Fig. 7) with those for S_1 (Fig. 6) seems to justify this prediction. On reducing the thickness, the CCD curves for S_1, in spite of sizable narrowing, retain essentially the same shape, whereas those for S_2 become progressively more asymmetric. This asymmetry (responsible for the increase of the exponent n) is associated with the development of rather narrow tail at the high current side of the CCD curve for sample

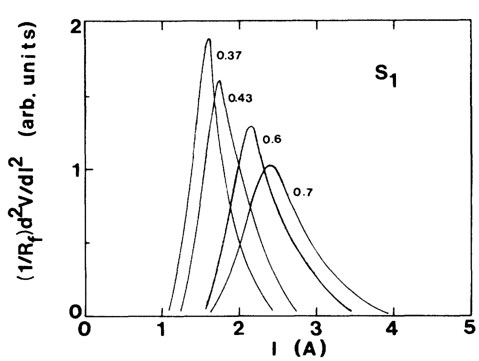

FIG. 6. Critical-current distributions at 80 K for different thicknesses, t, of sample S_1. The numbers denote, t, (in mm).

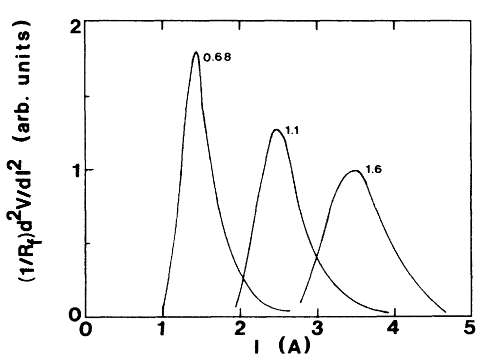

FIG. 7. Critical-current distributions at 80 K for different thicknesses, t, of sample S_2. The numbers denote t (in mm).

S_2 (Fig. 7). This tail shows that a small fraction of rather high critical currents, unlike I_c, does not scale to the cross section of the sample.

The results presented above show that, as is the case for the conventional type-II superconductors,[8] CCD curves of the ceramic Y-Ba-Cu-O samples are closely related to their microstructure. Hence, a recent suggestion that the self-field effects may mask such relation[9] seems unjustified. The results in Fig. 6 show that the complex changes in the self-field effects associated with the reduction of thickness of S_1 merely change a width but do not change the shape of the CCD curves for this sample. In particular, the ratios between I_{cp}, $\langle I_c \rangle$, I_{cm}, and I_c do not change with t, and the height of the CCD is proportional to $(W_F)^{-1}$. On the other hand, the results presented in Fig. 7 prove that any redistribution of current within the sample shows up in the shape of the CCD curve, irrespective of the change of the total I_c or the macroscopic parameters for that sample (Table I). Considering them together, these results indicate that a parallel investigation of the microstructural characteristics and CCD curves may be a very useful way for understanding the parameters limiting the critical currents in the bulk samples of high-temperature superconductors. Such studies for samples S_1, S_2, and S_3 are in progress.

IV. CONCLUSION

Systematic investigation of the influence of reduction of the sample's thickness (t) on critical currents (I_c) and their distributions (CCD) in two well-characterized polycrystalline Y-Ba-Cu-O samples with different average grain sizes $d_{g,\mathrm{av}}$ indicates that a complex pattern of the self-field effects exists in ceramic Y-Ba-Cu-O samples. According to our results and also to the results of other authors,[1,14,15] the effects of the self-field on I_c and CCD depend, in general, on both, $d_{g,\mathrm{av}}$ and t. Three regimes characterized by the different variations of I_c and CCD with t can be identified.

(i) In the first regime the self-field is independent of t and $I_c \propto (w+t)$, i.e., $J_c \propto (w^{-1}+t^{-1})$ for a platelike sample. A plausible explanation of such behavior can be found in an effective cancellation of the self-fields of the adjacent currents flowing in parallel in the interior of sample. Thus, a macroscopic self-field flows mainly at the surface of the sample. In a sample with very fine and uniform grains, such behavior may persist down to quite low t (Ref. 1), and hence lead to the large increase in J_c. This may probably explain the large values of J_c reported for some samples with very fine grains.[1,14,15] Our samples obviously do not belong to this class.

(ii) In the transitional regime, the macroscopic self-field seems to still exist, but its magnitude decreases somewhat with thickness of a sample. This behavior occurs when the grains are somewhat larger and/or the ratio $t/d_{g,\mathrm{av}}$ is not too large. Under these conditions a less effective cancellation of the individual self-fields is highly probable. In this regime (realized in S_1 for $t > 0.43$ mm), I_c decreases somewhat faster (hence, J_c increases slower) with t than in conditions of the first regime.

(iii) Finally, when the grains become quite large and/or $t/d_{g,\mathrm{av}}$ becomes moderate, the description in terms of the macroscopic self-field seems entirely inappropriate. Initially (i.e. for t not too small), I_c is proportional to the cross-sectional area (hence, J_c is independent on t), which can be ascribed to the conduction by the independent parallel currents in the macroscopically homogeneous sample (S_2). However, when t becomes comparable to $d_{g,\mathrm{av}}$, I_c will depend on the local properties of the remains of the sample; hence, the variations of I_c and J_c with t may become haphazard.[15]

The different self-field regimes should also show up in CCD curves. In the first regime we expect the shape and the relative width of the CCD curve $(W_F/\langle I_c \rangle)$ to be independent of t. The main difference in the transitional regime would be that $W_F/\langle I_c \rangle$ may decrease with t. In the last regime the thinning of the sample should ultimately lead to a change in the shape of the CCD associated with the local properties of the sample.

The above plausible explanation, based on our results for samples S_1, S_2 (and S_3), and some previous reports,[1,14,15] should be verified on more ceramic samples with very different $d_{g,\mathrm{av}}$ and, whenever possible, with known grain size distributions. Such experiments may improve the knowledge of the nature of critical-current limitations in bulk high-temperature superconductors.

Finally, we wish to note that the t- and $d_{g,\mathrm{av}}$- dependent effects described above clearly indicate a percolative nature of the critical-current flow in ceramic Y-Ba-Cu-O samples.[18] Within this picture, the observed behaviors can be associated with the variation (disorder) in the intergrain couplings and thus with the microstructural features of the samples. In particular, in the case of a strong disorder (a large variation in the quality of the intergrain coupling) in three-dimensional (3D) geometry, the individual conduction regime would be more likely to occur than in the case of a weak disorder. The morphology of the grains and the grain boundaries for our samples S_1 and S_2 (Fig. 1) supports that view. Furthermore, when t approaches $d_{g,\mathrm{av}}$, distinct 2D percolative effects can be expected. Because of that, as mentioned above, detailed microstructural investigations of the samples may prove as very important.

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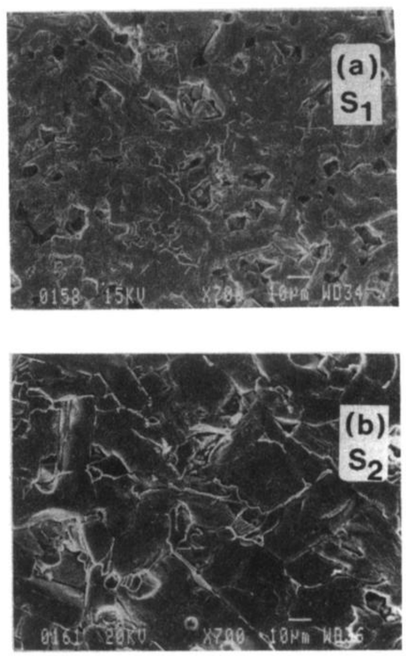

FIG. 1. SEM of $YBa_2Cu_3O_{7-x}$ (a) sample S_1 sintered for 7 h and (b) S_2 sintered for 70 h.