Nature of the large critical current in textured high-T_c yttrium metal oxide ceramics

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We investigate the influence of hydrostatic pressure on the superconducting transition temperature T_c and the critical current density j_c of a textured YBCO ceramic fabricated by the MTG method with $j_c = 4.2 \cdot 10^4$ A/cm^2 ($H = 0$), $j_c = 8 \cdot 10^3$ A/cm^2 ($H = 10$ kOe) at a temperature $T = 77$ K. In textured samples, the reaction of j_c to pressure p ($d \ln j_c/dp = 0.02$ kbar^{-1}) turns out to be considerably smaller than the value of $d \ln j_c/dp = 0.1$ kbar^{-1} which is characteristic for the yttrium ceramics prepared using the usual technology. The overall increase in critical current in the MTG samples is explained by the observed value of $dT_c/dp = 0.3$ K/kbar. This allows us to conclude that Josephson weak links, which are also present in the textured ceramics, do not manifest themselves in the current characteristics of the latter.

Examination by electron microscope has shown that there is considerable damage to the crystalline structure of yttrium ceramics even for small-angle boundaries between crystalline grains, while, as was shown in Ref. 1, the removal of even a single atomic layer normal to the **c**-axis leads to such structural damage that the near-surface layers can no longer be superconducting. In textured samples the boundaries are easily observed by ordinary optics, and during strain the lines of cleavage run along them. Therefore the presence of weak links in these samples is unarguable. The usual evidence for formation of a network of weak-link contacts in a sample is the strong response of its critical current density j_c to a weak (~ 100 Oe) magnetic field. However, this test is effective only when the self-field of the current in the sample does not produce any appreciable distortion of the function $j_c(H)$. Furthermore, in Josephson media the critical current can itself depend weakly on fields $H \geqslant 100$–200 Oe (Ref. 2). Therefore, low sensitivity of j_c to magnetic field in textured samples still does not prove that the current flowing in the sample is of non-Josephson character. Meanwhile, clarification of the mechanism of current flow is important for analyzing the character of flux pinning in the samples and choosing a technological direction to pursue.

Previous work has established that $j_c(p)$ increases rapidly with pressure p for ceramic samples, which is explained by the high sensitivity of the critical current of the Josephson contacts to strain in the intergranular layers.[3] In this paper we will investigate the response of the transport properties of a sample of textured ceramic to hydrostatic pressure and magnetic field. The results of our investigation allow us to draw conclusions regarding the character of current transport in MTG structures.

Experiment

Samples of yttrium ceramic with a pronounced texture (Fig. 1) were made from 123-ceramic by the method of directed growth in a temperature gradient (MTG).[4] The original ingots were obtained by the usual method of solid-phase synthesis. After this they were heated to $T = 1150$ °C and maintained there for 10 minutes at this temperature. They then were cooled in a temperature field with gradient 20–25°/cm at a rate of 3°/hour in the range 1050–950 °C, and then saturated with oxygen at a temperature 450 °C over the course of 5–10 hours. It is noteworthy that the ceramics obtained in this way are highly brittle and exhibit a considerable amount of internal stress, which may explain the cracking that such samples are often subject to when they undergo mechanical processing.

In order to investigate the electrical characteristics, bridge-type samples were cut from ceramic ingots with a diamond disk; the bridge samples had a constriction with dimensions $0.15 \times 0 \cdot 15 \times 3$ mm^3. The low-resistance contact areas were obtained by brazing with silver. It should be noted that the task of fabricating high-quality contacts on textured samples is quite involved, because in many cases during attempts to solder, the contact areas peel off together with the ceramic layer. Nevertheless, we succeeded in obtaining current contacts with rather small ($R_c = 10^{-3}$ $\Omega \cdot$cm^2) resistance, making it possible for us to operate at current densities $j_c \sim 4 \cdot 10^4$ A/cm^2 without heating effects.

The inset to Fig. 2 shows how the resistive $R(T)$ transition changes when the sample is subjected to hydrostatic pressure $p = 8$ kbar by placing it in a piston-cylinder type

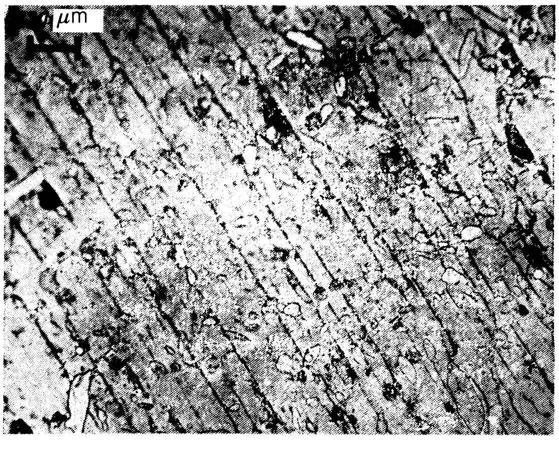

FIG. 1. A photograph of an etched stub of ceramic obtained by the MTG method.

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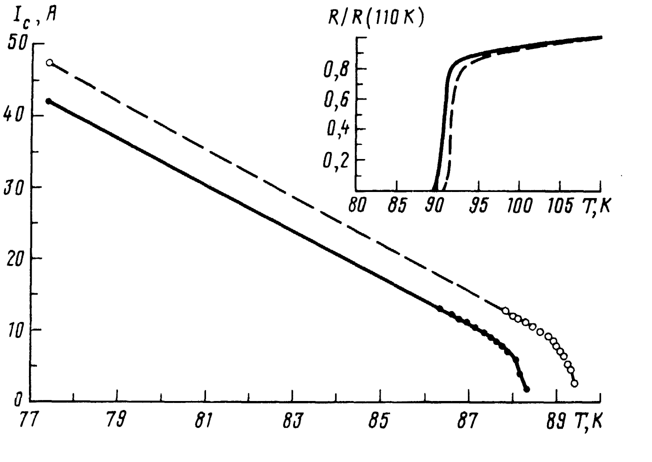

FIG. 2. Temperature dependence of the critical current of textured $YBa_2Cu_3O_7$ ceramic $I_c(T)$ under a pressure $p = 1$ kbar (●) and $p = 9$ kbar (○). In the inset: Superconducting $R(T)$ transition under pressures $p = 1$ kbar (solid curve) and $p = 9$ kbar (dashed curve).

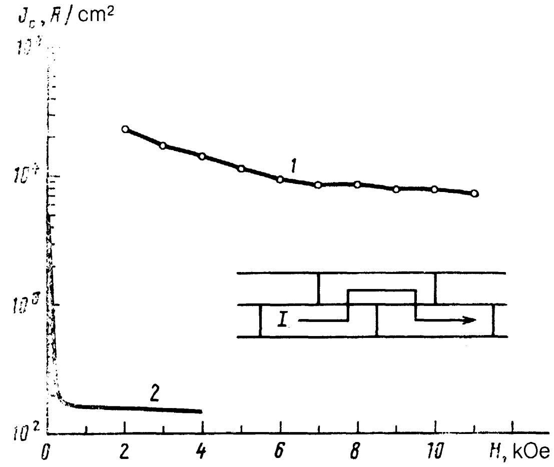

FIG. 3. A comparison of the dependence of the critical current density J_c (in logarithmic coordinates) on magnetic field H for textured (1) and normal (2) 123-ceramics. Inset: Illustrates the flow of current in a texture of the "brick masonry" type.

chamber. In order to determine the temperature precisely, a thermometer made of a thin (0.02 mm) copper wire was placed inside the chamber channel in the immediate vicinity of the sample. The value $dT_c/dp = 0.3$ K/kbar was found to be considerably larger than for the untextured 123-phase, for which $dT_c/dp \cong 0.03$ K/kbar (Ref. 3). This fact may be ascribed to the oriented state of the sample, for which anisotropy effects manifest themselves most strongly, or to the obvious presence of other phases (Fig. 1). Measurement of critical current in the high-pressure chamber was made more complicated by the small cross section of the wire in the obturator. Therefore, the measurements of $j_c(p)$ were carried out near T_c. Extrapolation of the critical current to a temperature $T = 77$ K and direct measurements of j_c outside the high-pressure chamber gave a value for the critical current density $j_c(T = 77\ \mathrm{K}) = 42$ kA/cm^2 in the absence of an external magnetic field (Fig. 2).

The behavior of the critical current in a magnetic field is shown in Fig. 3. The weak dependence of $j_c(H)$ that we observe for the textured ceramics is in sharp contrast to the $j_c(H)$ characteristics of an ordinary ceramic sample, although initial current densities for the two ceramic types may be close (Fig. 3). The difference lies in the pressure response of the two types: for pressures in the range 8–10 kbar j_c changes by only 15–20%, whereas for ordinary 123-ceramics an increase in j_c of 100% or more is characteristic. This small increase in $j_c(p)$ for the textured ceramics is entirely explained by the growth of the critical temperature with pressure (Fig. 2).

Discussion of results

Based on expressions that describe various pinning mechanisms for Abrikosov vortices,[5] we find that the following relation holds

$$j_c(B,\ T) = q(B,\ T)(T_c - T)^m, \tag{1}$$

where the exponent $m = 3/2$–2. The factor q depends on the pressure through the parameters $N(0)$ and D, which are associated with the electronic characteristics of the metal, while the variation of the geometric parameters with pressure is proportional to the compressibility $\varkappa$. In the metal ceramics the coefficient of bulk compressibility $\varkappa$ is very small [$\varkappa = (5 \cdot 10) \cdot 10^{-4}\ \mathrm{kbar}^{-1}$; see Ref. 6]. The density of states $N(0)$ and the diffusion coefficient D are related to the conductivity via $\sigma_N \sim N(0)D$. Experiment shows a comparatively weak increase in the conductivity of the metal oxides with pressure ($d\ln\sigma_N/dp \cong 0.003\ \mathrm{kbar}^{-1}$). The derivatives $d\ln N(0)/dp$ and $d\ln D/dp$ cannot exceed this value. As a result the dependence of the parameter q on pressure is proportional to $\varkappa$ and the primary contribution to $d\ln j_c/dp$ is given by the term $m(T_c - T)^{-1} dT_c/dp$. Therefore, if the critical currents $j_c(0)$ and $j_c(p)$ remain close to one another during a parallel shift of the $j_c(p) - T$ dependence by the difference $\delta T_c = T_c(p) - T_c(0)$, which we do in fact observe in the textured 123-ceramic, we can argue that the usual pinning mechanisms are occurring in the ceramic.

The pressure response of the critical current associated with a network of Josephson contacts, i.e., a Josephson medium, can differ strongly from this picture. In this case the critical current density $j_c \sim I_c/L_0^2$, where L_0 is the size of a cell of the contact network and I_c is the critical current of the Josephson contact. The critical current for a Josephson contact can be written in the form

$$I_c \sim \frac{1}{R_{Nm}} \left[\frac{T_c - T}{T_c}\right]^m \exp(-\zeta), \tag{2}$$

where R_{Nm} is the resistivity of the metallic part of the contact in the normal state and the exponent $m = 1$–2. For contacts of S–I–S type, the exponent $\zeta = d_I \varphi^{1/2}$, where d_I is the thickness of the insulator I and φ is the height of the potential barrier. In a contact with normal (N) layers of type S–N–S we have $\zeta = d_N/\xi_N$, where d_N is the width and ξ_N the coherence length in the N-layer. The fundamental difference between the pressure response of the critical current of a network of Josephson contacts and that of a pinning current in an ordinary superconductor (1) is the presence of the exponential factor $\exp(-\zeta)$, which reflects the weak overlap of the wave functions across the superconducting bridges of the Josephson contacts. Including the exponential factor

$\exp(-\zeta)$, the formula that describes the pressure response of the critical current has the following general form

$$\frac{d\ln j_c}{dp}=\frac{d\ln q}{dp}+\frac{mT_c}{(T_c-T)}\frac{d\ln T_c}{dp}-\zeta\frac{d\ln\zeta}{dp}. \qquad (3)$$

In the YBCO ceramic the structure of planar defects at the atomic level is such that the contacts that are predominantly realized include an insulating layer (*S–I–S*, SNINS, etc.).[1,7] Therefore, the parameter ζ is large ($\zeta \geqslant 10$), and the "Josephson" term $\zeta d\ln\zeta/dp$ makes a significant contribution to the increase of the critical current of the contacts with pressure.[3] This being the case, why should the effect of this term not appear in the textured samples under discussion here?

In our view the decisive factor is the significant change in the character of current flow in the textured ceramics compared with ordinary ones. In a dense ceramic, whose grains have dimensions l_{ab} along the **ab** plane that considerably exceed its transverse size d_c (along the **c**-axis), the grains make contact predominantly across their wider surfaces, i.e., along planes that are parallel to the plane **ab**. In such a case, the "overflow" channel is the primary contributor to the transport current. This implies that the contact between adjacent grains A and B located in the **ab** plane is made with the help of a grain C which overlaps both granule A and granule B (this involves a "brick masonry" type of pattern; see inset of Fig. 3). The role of the end contacts, which are located in the plane **ab** can in this case turn out to be insignificant, and the primary current from A to B flows along the path $A\rightarrow C\rightarrow B$. The Josephson contacts, which are located along such an "overflow" current path, are formed by small-angle boundaries (normal to the **c**-axis), which, as is well-known,[7] corresponds to the optimum conditions for attaining maximum critical current density J_{cJ} through a boundary between ceramic grains. However, the advantage of the "brick masonry" type of structure does not rest simply in this. Because of the "overflow" current along the path $A\rightarrow C\rightarrow B$, the density of the Josephson critical current J_{cJ} is effectively increased by a factor of l_{ab}/d_c, which in order of magnitude corresponds to the ratio of the area of the wide surface of the grain $s_c \sim w\cdot l_{ab}$ to the cross sectional area $s_{ab}\sim w\cdot d_c$ of the ends (w is the width of the grain).

This effective increase in the critical current density of the Josephson contacts in a textured sample can lead to a situation where the value of the latter exceeds the critical current density J_{cg} of the grains themselves

$$(l_{ab}/d_c)J_{cJ}>J_{cg}, \qquad (4)$$

i.e., the Josephson current flows through a surface whose area greatly exceeds the cross sections of the ends. As a result, e.g., for a ratio $l_{ab}/d_c\sim 100$ and $J_{cJ}\sim 100$ A/cm^2, condition (4) implies that $J_{cg}<10$ kA/cm^2. It has been established experimentally (for nontextured ceramic samples) that in YBCO ceramics the density of critical current of the Josephson contacts $J_{cJ}(H)$ drops rapidly as the magnetic field H increases; however, in fields $H\geqslant H_{c1g}$ the variation of $J_{cJ}(H)$ slows down, and values of $J_{cJ}(H)\sim 100$–500 A/cm^2 are preserved[2] up to fields $H\sim 15$ kOe. Therefore, in textures of the "brick masonry" type it is possible to preserve the critical current density $J_c\sim 50$ kA/cm^2 up to $H\sim 15$ kOe if the grains are sufficiently extended in the **ab** plane ($l_{ab}/d_c\geqslant 100$).

Microscopic investigations show that for our case we have $l_{ab}/d_c\sim 30$; therefore, the critical current density of $J_c\sim 10^4$ A/cm^2 we observe in a high field $H\sim 10$ kOe is not incompatible with preservation of the Josephson links between grains normal to the **c** axis if their critical currents in fields $H\sim 10$ kOe are on the order of 300 A/cm^2. In this case condition (4) can be fulfilled, and the critical state in the ceramic arises as a result of the transition of the grains themselves to the resistive state, i.e., $J_c\cong J_{cg}$. In this case the response of the critical current to the pressure p will essentially be determined by the change in $T_c(p)$ (compare Eq. (3) without the term containing ζ).

Thus, by fabricating structures like the ones under study here, i.e., laminar structures with thin grains that are extended along the **ab** plane, we can ensure an "overflow" current whose characteristics mask the presence of weak links in the ceramic samples under ordinary transport measurements. This explains the observed difference in character of the pressure response of the critical currents for normal and textured yttrium ceramics.

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