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PHYSICA C

Physica C 234 (1994) 368–372

Magnetic hysteresis of the zero-resistance critical temperature in $YBa_2Cu_3O_{7-x}$ ceramic superconductors

L.E. Flores, E. Altshuler, S. García, J. Musa

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Received 11 October 1994

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Subscription data

Physica A (ISSN 0378-4371). For 1994, volumes 201–211 are scheduled for publication. Physica A is published semimonthly.
Physica B (ISSN 0921-4526). For 1994, volumes 192–202 are scheduled for publication. Physica B is published monthly.
Physica C (ISSN 0921-4534). For 1994, volumes 219–236 are scheduled for publication. Physica C is published two to three times per month.
Physica D (ISSN 0167-2789). For 1994, volumes 70–78 are scheduled for publication. Physica D is published semimonthly.
Subscription prices are available upon request from the publisher. A combined subscription to Physica A, Physica B, Physica C and Physica D is available at a reduced rate.

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Printed in The Netherlands

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Magnetic hysteresis of the zero-resistance critical temperature in $YBa_2Cu_3O_{7-x}$ ceramic superconductors

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Abstract

We have found noticeable hysteretic behavior in the dependence of the zero-resistance critical temperature obtained through resistivity (ρ) vs. temperature (T) measurements with applied field (H_e) in $YBa_2Cu_3O_{7-x}$ ceramic superconductors. This behavior is qualitatively explained based on the analogy between the present phenomenon and the analogous hysteresis observed in the transport critical current (J_c) vs. H_e curves of these materials.

1. Introduction

The resistive transition to the superconducting state in $YBa_2Cu_3O_{7-x}$ superconducting ceramics occurs via two intermediate stages: the first one takes place at the so-called *onset temperature* or *intrinsic onset temperature* [1] (T_{c0}) and consists in a sharp drop of the resistivity when the grains become superconducting. At that stage, there is a strong phase disorder between grains, i.e. the weak links between them give non-zero resistance across the sample. If the temperature is further decreased, the inter-grain coupling energy gradually overcomes the thermal one, in such a way that the sample finally enters into a zero-dissipation (or zero-resistance) state. The temperature at which this takes place is currently called *coupling critical temperature* [1], *critical temperature* [2] or *zero-resistance critical temperature* (T_c). In this work T_c is taken as the temperature value for which $\ln(\rho/\rho_0)=-6$ (about x nV with a 0.5 mA bias current) where ρ_0 is the resistivity at the onset temperature.

It is well known that an external magnetic field affects both T_{c0} and T_c. However, for small values of H_e ($H_e<24000$ A/m (300 Oe)) there is no sensible affection of T_{c0}. In this work we supposed that T_{c0} does not depend on H_e (which is not far from reality) so we will focus our attention on the variation of T_c with H_e.

Although the dependence of T_c with a magnetic field has been studied for increasing values [2], we did not found any report in the literature on its dependence for decreasing ones. In this work the results of measurements for both increasing and decreasing fields and their qualitative explanation using a model based on the effect of the flux trapped inside the superconducting grains on the inter-grain junctions [3], is given.

2. Experimental

$YBa_2Cu_3O_{7-x}$ samples were prepared by the standard ceramic technique. The pressed pellets were sintered at 950°C for 16 h and cooled down to room temperature in an oxygen flow at a rate of 1°C/min. Bars of approximate dimensions $10\times1\times0.2$ mm^3

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SSDI 0921-4534(94)02325-5

were cut from the pellets suitable for four-probe measurements. The $\rho(T)$ measurements were made through the well known four-terminal technique with an AC excitation signal provided by a common mode nulling current source which minimizes the effects of the common mode signals in the voltage probes and allows the measurement through a lock-in amplifier with a zero foot of less than 1 nV even with contact resistances up to 100 Ω (contacts made with silver paint). The bias current had a value of 0.5 mA which minimized the resistive tails produced by self-fields. The $J_c(H)$ measurements where made using a dynamic current source controller [4] which allows a faster and accurate measurement of those dependences. The magnetic field was generated by a solenoid and was applied perpendicular to the excitation current. The resolution of the temperature measurements was 0.1 K.

In all cases, the sample was zero-field cooled (ZFC) down to 77 K. In the case of increasing-field measurements ('virgin-curve'), the desired value was set directly from zero. For decreasing-field measurements ('returning-curves'), a maximum value (H_m) was firstly applied and then decreased to the desired one. All the process of variation and stabilization of field was carried out by the host computer in order to avoid variations between different measurements, due to flux creep processes. The temperature was then swept from 80 to 110 K at a 1 K/min rate which allowed the lock-in amplifier, with a time constant of 300 ms, to follow the voltage variations with the necessary accuracy. The process explained above was repeated several times in order to obtain the $T_c(H_e, H_m)$ dependence. The $J_c(H_e, H_m)$ dependences where obtained at 77 K (liquid nitrogen temperature).

3. Results and discussion

The measurements of $\rho(T)$ for different increasing fields (Fig. 1) show the double-transition character previously observed in granular superconductors [5,6] as well as the appearance of field-induced tails even for small values of the field, which can be explained in terms of inter-grain field penetration [2].

The measurements of $\rho(T)$ for decreasing fields (H_m>4000 A/m (50 Oe)) do not show the character mentioned above. This might be explained in terms of the effect of the field trapped by the grains on the inter-grain junctions [3], which never allows them to 'feel' a very low magnetic field (close to $H=0$) as in the case of the increasing-field $\rho(T)$ curves.

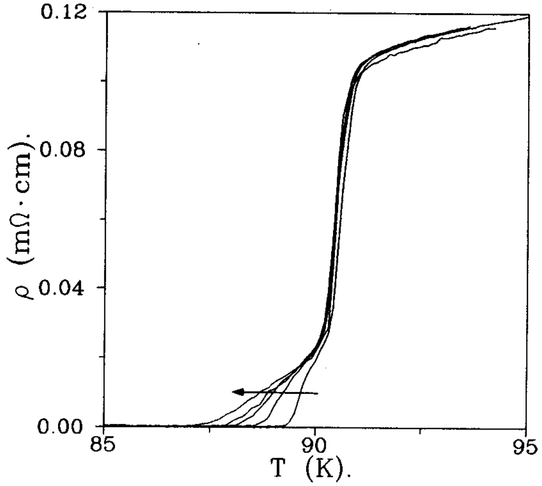

Fig. 1. Temperature dependence of the electrical resistivity of $YBa_2Cu_3O_{7-x}$ for selected increasing fields (the applied fields in the direction of the arrow are 0, 5, 10, 15, 20 and 25 Oe).

The dependence of T_c with H_e was obtained by fitting the expression [5],

$$\rho=\rho_0 \exp\left(\frac{U(H,T)}{T}\right)=\exp\left[\frac{U_0(H)}{T}\left(1-\frac{T_{c0}}{T}\right)^{\alpha}\right], \quad (1)$$

to the experimental curves, where $U_0(H)$ is the activation energy.

Fig. 2 shows the dependence of T_c vs. H_e for increasing values of H_e which has the same character previously observed in polycrystalline $YBa_2Cu_3O_{7-x}$ [2]. The sensitivity of T_c for small values of H_e (H_e<400 A/m (5 Oe)) can be explained in terms of the weakening of the inter-grain coupling energy due to inter-grain field penetration.

Fig. 3 displays the same dependence for decreasing fields which shows an hysteretic behavior not reported previously in the literature to our knowledge. We have found similar features in other samples studied in less detail. This behavior can be explained by extending to our case the qualitative model firstly developed by Evetts and Glowacki to explain the magnetic hysteresis of the transport critical current density vs. field curves $J_c(H_e)$ [3,7]. This model is

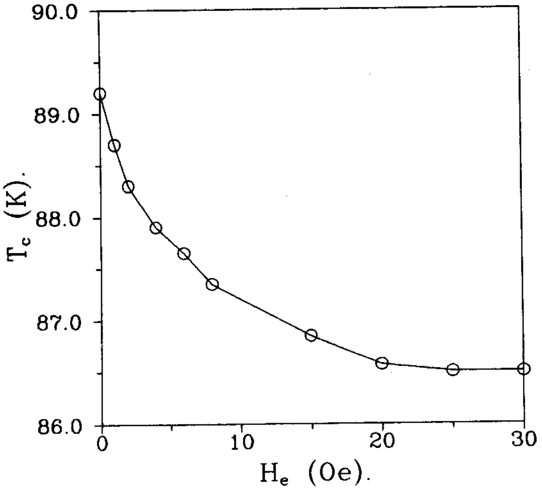

Fig. 2. $T_c(H_e)$ characteristics for increasing fields.

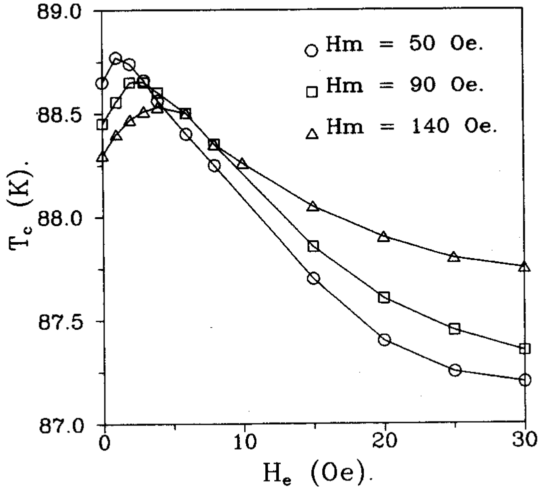

Fig. 3. $T_c(H_e, H_m)$ characteristics when the external field decreases from 50, 90 and 140 Oe.

based on the effect of the flux trapped by the superconducting grains on the inter-grain weak links, which controls the mechanism of current transport, in such a way that a minimum in the effective field (external field plus the field associated to grain magnetization) at the junctions provokes a maximum in the J_c vs. H_e curve for decreasing fields. Since T_c is strongly dependent on the junctions' characteristics, it is not surprising, in principle, to expect a hysteretic behavior in T_c analogous to the one observed in $J_c(H_e, H_m)$.

To put it in more quantitative terms, we can accept that the dependence $J_c(T)$ has the form $J_c \approx (1-T/T_{c0})^q$ where q is a fitting parameter [8–10], but if we assume that our sample behaves like an assembly of grains linked by classical Josephson S–I–S-type junctions, then J_c is proportional to $U(T, H)$ [5] and we can make $q=\alpha$ (see Eq. (1)), so the dependence of J_c on T is:

$$J_c = J_{c0}(H_e)\left(1-\frac{T}{T_{c0}}\right)^{\alpha}, \tag{2}$$

where J_{c0} is the critical current density at $T=0$. This expression is valid for the $J_c(H_e, T)$ virgin characteristic (Fig. 4), but to extend this expression to the $J_c(H_e, H_m, T)$ returning curves (Fig. 5) we must analyze all the elements determining J_{c0}. For example, the shape of these curves depend on grain magnetization [4,7]. In fact, the effective field felt by the junctions can be modelled by [7]

$$H_{\text{eff}} = H_e - GM(H_e, H_m, T)\ . \tag{3}$$

It should be noted that, if after setting the desired field value, the temperature is raised, the magnetization decreases and according to (3) the compensation between H_e and $GM(H_e, H_m, T)$ (i.e. the field value at which H_{eff} is a minimum) shifts to lower values in the H_e-axis, than the ones expected for a fixed T, as happens in the experiments commonly reported involving the $J_c(H_e)$ hysteresis [7]. Taking into account expression (3) we have to modify (2) in the following way:

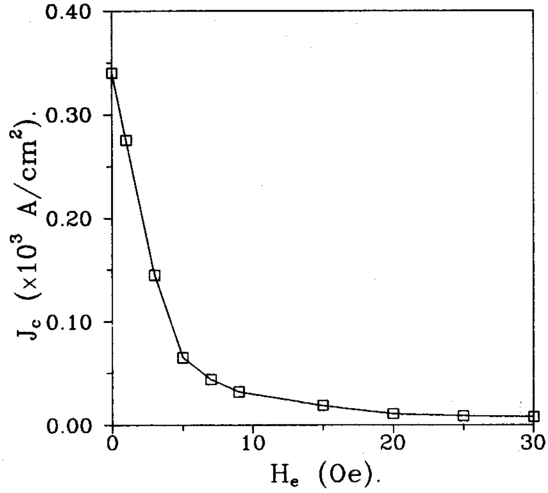

Fig. 4. $J_c(H_e)$ characteristics for increasing fields.

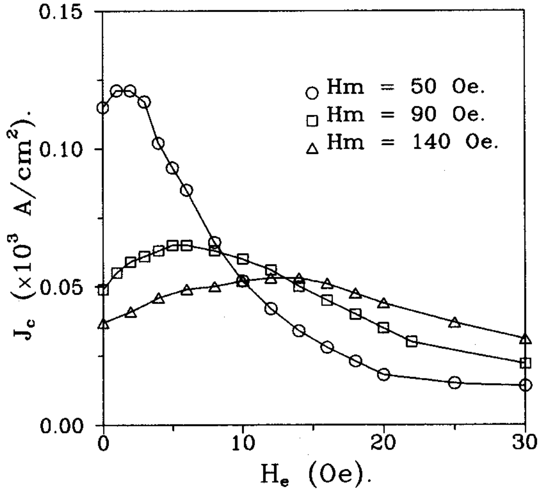

Fig. 5. $J_c(H_e, H_m)$ characteristics when the external field decreases from 50, 90 and 140 Oe.

$$J_c = J_{c0}(H_{eff}) \left(1 - \frac{T}{T_{c0}}\right)^{\alpha}. \quad (4)$$

According to this expression when T is raised J_c not only decreases by the factor $(1 - T_c/T_{c0})^{\alpha}$, but the peak position in the $J_c(H_e)$ curves is shifted to the left in the H_e-axis.

If we assume that when T_c is reached the bias current density (J_m) equals J_c (J_c defined as the minimum current density at which the sample shows dissipation in the form of voltage) the expression for T_c from Eq. (4) is:

$$T_c = T_{c0}\left[1 - \left(\frac{J_m}{J_{c0}(H_{eff})}\right)^{1/\alpha}\right] = T_{c0}\left[1 - \left(\frac{J_m}{J_{c0}(H_e, H_m, T_c)}\right)^{1/\alpha}\right]. \quad (5)$$

To obtain a simpler expression for the $J_c(H_e)$ dependence it is convenient to take some approximations to eliminate T_c from the J_{c0} argument. Substituting $J_{c0}(H_e, H_m, T_c)$ by its dependence at some temperature slightly below the lowest T_c given by the experiment (T'_c), we obtain a $T_c(H_e, H_{eff})$ dependence in which the field value where the $J_c(H_e)$ peak appears is slightly shifted to right in the H_e-axis:

$$T_c = T_{c0}\left[1 - \left(\frac{J_m}{J_{c0}(H_e, H_m, T'_c)}\right)^{1/\alpha}\right]. \quad (6)$$

In principle, any quantitative model used for the fitting of the $J_c(H_e, H_m)$ dependence (for example the one proposed in Ref. [7]) can be used for the $T_c(H_e, H_m)$ characteristic if the relation (6) is respected and with an adequate selection of T'_c, T_{c0} and α. It is clear from Eq. (6) that, provided $J_c(H_e, H_m)$ is hysteretic, $T_c(H_e, H_m)$ is hysteretic too. In particular, the peaks observed in $J_c(H_e, H_m)$ (Fig. 5) imply the existence of a similar feature in the $T_c(H_e, H_m)$ returning curves (Fig. 3), at lower values of H_e, as we have seen in the experiment.

4. Conclusions

We have found a notorious irreversibility in the $T_c(H_e, H_m)$ behavior of $YBa_2Cu_3O_{7-x}$ superconductors characterized by a maximum in the decreasing-field characteristic.

The comparison with the analogous irreversibility in the transport $J_c(H_e, H_m)$ curves showed that there is a clear connection between both phenomena, as can be expected from the model originally proposed by Evetts and Glowacki [3] dealing with the hysteresis of the local inter-grain field of these materials provided some new T-dependent effects are introduced. Taking into account the $J_c(H_e, H_m, T)$ dependence, we have demonstrated to a first approximation the relation between the model mentioned above and the observed hysteresis in $T_c(H_e, H_m)$.

Finally, it may be stressed that, perhaps, the hysteresis of T_c might be an interesting tool for the study of the local fields at the inter-grain junctions since it is not affected by the self-fields of the same extent as the J_c hysteresis experiments because of the very small values of the bias current involved in T_c measurements.

Acknowledgements

We gratefully acknowledge C. Trallero and M. Octavio for their valuable comments, and A. Aguilar for providing the $YBa_2Cu_3O_{7-x}$ ceramics. This work was partially supported by the Third World Academy of Sciences, through Research Grant No. 92-058.

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