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RADIO-FREQUENCY SURFACE IMPEDANCE OF HTSC-CERAMICS AND DEFINITION OF CRITICAL CURRENT DENSITY

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The dependence of local critical current density j_c on the magnetic field H is obtained by use of the low frequency electromagnetic probe signal. It is shown , that in a wide region of magnetic field the value of j_c is proportional to $H^{-3/2}$ for the YBCO ceramic samples with different structure.

1. HTSC-ceramics is known to be a system consists of the superconducting grains which connected by Josephson weak links. The electromagnetic properties of the ceramics is considerably determined by correlation between typical size a of structure sell and Josephson penetration depth λ_J. In coarse-grained medium where

$$\lambda_J << a \qquad (1)$$

the magnetic flux exists in form of Josephson vortices located in the intergranular contacts. In fine-grained ceramics where

$$a << \lambda_J \qquad (2)$$

the magnetic flux quantum envelopes the large number of contacts. In this case the system of hypervortices is formed in ceramics (see,for example, [1-2]).

Despite the principal difference of situations (1) and (2), in both cases the electrodynamical properties of high-T_c ceramics are well described by the critical state model in a rather wide range of magnetic field H < 100 Oe [1,3-5] (see also [6-8]). In this model the electromagnetic field distribution in a sample is determined by the equation

$$c\cdot \mathrm{rot}\mathbf{B} = 4\pi\mu j_c \mathbf{E}/E. \qquad (3)$$

Here **B** is the vector of magnetic induction, **E** is electric field, μ is the magnetic permeability of ceramics without Josephson weak links between the grains, j_c is the critical current density. It is extremely important, that critical current density of the ceramics is very sensitive to the magnetic field:

$$j_c = j_c(B). \qquad (4)$$

It is necessary to emphasize, that various ceramic samples differ each other by magnitude j_c and by its dependence on B. Namely the difference of physical situations (1) and (2) may effect on the form of material equation (4). Therefore definition of the function $j_c(B)$ is one of the major problem in description of electromagnetic properties of ceramics. Moreover, this problem has also practical interest because the value of macroscopic critical current is connected with relation (4).

2.The traditional methods of determination of dependence $j_c(B)$ in ceramics based, as a rule, on measurement of a critical value of the full transport current I_c as a function of an external magnetic field. But such a way has serious fails. The point is that in such kinds of measurements it is impossible to neglect a self-magnetic field of the electric current[1]. Since this field is inhomogeneous, the critical current density j_c proves to be a function of coordinates and full measured current I_c, that contains an information about average critical current density defined not only by external magnetic field but by a self-field too. In addition this method is not suitable because of the necessity to use the electric contacts.

The contactless method of determination of function $j_c(B)$ was proposed in[9] by use of a probe ac magnetic field in presence of an external static magnetic field. The method based on the measurement of the surface impedance $\mathcal{Z}$ of a sample. The surface impedance is defined by relation

$$\mathcal{Z} = -(8\pi/c)\cdot E_{\omega}(R)/h,$$
$$E_{\omega} = (\omega/2\pi)\cdot\int_0^{2\pi/\omega} dt\ E(R,t)e^{i\omega t} \qquad (5)$$

Here h is an amplitude of an external ac magnetic field having a form

$$h(t) = h \operatorname{Cos} \omega t, \qquad (6)$$

ω is a circular frequency , $E(R,t)$ is an electric field on a surface of cylinder with radius R. Both external static and alternating fields H and h are oriented along axis of cylindrical sample.

In the case when the amplitude of alternating field is so small that the dependence of j_c on h is negligible, the surface impedance $\mathcal{Z}$ is described by the formula:

$$\mathcal{Z}=(2/3\pi)\cdot\{\mu\omega h/[cj_c(\mu H)]\}\cdot(1-3\pi/4). \qquad (7)$$

It follows from (7) that the impedance is proportional to j_c^{-1}. The physical nature of this result is quite clear. The whole point is, that the surface impedance is proportional to penetration depth δ of electromagnetic field into a sample. In conditions

$$h \ll B^*/\mu, \text{ or } h \ll H \qquad (8)$$

(B^* - the typical scale of function $j_c(B)$ changing) the current density j_c does not depend on ac magnetic field, so the penetration depth δ of signal is determined as $\delta \simeq h/j_c$. This correlation is present in (7) in evident form. Note, that the formula (7) should be correct, it is necessary to keep following condition

$$h \ll 16\pi j_c(\mu H)R/c, \qquad (9)$$

which equivalent to the inequality $\delta \ll R$. This condition limits the region of magnetic field H from above because the current density j_c decreases with increase of H.

So by measurement of surface impedance in conditions (8) and (9) one can determine the dependence $j_c(\mu H)$. This dependence as mentioned in[10] can be defined by measurement of other value - ac magnetic susceptibility connected with impedance by simple linear relation

$$4\pi\chi = i[c^2/(2\pi\omega R)]\cdot\mathcal{Z} - 1. \qquad (10)$$

3.In this paper we realized proposed in[9] method of critical current density $j_c(B)$ measurement. Cylindrical YBaCuO ceramic samples with different size of grains were studied. The following discussion will be conducted for two samples with essentially different structure.For the fine-grained sample with radius R = 0.25 cm and average grain size $a \simeq 1\mu m$ the condition (2) is carried out, while for the coarse-grained one with R = 0.45 cm and $a \simeq 10\mu m$ the parameters a and λ have the same order of value. The real and imaginary parts of impedance were measured by the method described in[10]. The peak-up coil was wounded directly on a sample by copper wire 30 μm in diameter. An alternating magnetic field was created by the copper wire solenoid. The sample was immersed in liquid nitrogen. The peaked up signal, which is proportional to real $\mathcal{R}$ and imaginary $\mathcal{X}$ parts of surface impedance, was detected by the lock-in amplifier PAR-124A. The amplitude h of ac magnetic field was approximately 1 Oe. For this amplitude the inequalities (8) and (9) are carried out. The part of measured signal connected with the magnetic flux change in the clearance between the pick-up coil and the sample was compensated.

The dependence of impedance vs H for the fine-grained sample is presented on fig.1. The results were obtained at frequency $\omega/2\pi$ = 1 kHz in the region of magnetic field H from 0 to 80 Oe. The values $\mathcal{R}$ and $\mathcal{X}$ were measured in units $\mathcal{X}_n$, where $\mathcal{X}_n$ is reactance of the sample in the normal state:

$$\mathcal{X}_n = 2\pi R\omega/c^2 \qquad (11)$$

It is seen that in the full range of magnetic field change the values $\mathcal{R}$ and $\mathcal{X}$ increase monotonically. These dependences correspond to decrease of critical current density j_c with B or, in other words, to increase of the penetration depth δ of signal. It was found that the ratio $\mathcal{X}/\mathcal{R}$ is equal to 2 in the full range of magnetic field H. The deviation does not exceed 3%. The theoretical ratio ($3\pi/4$) is 20% higher than experimental one. This deviation may be connected with magnetic flux creep which we did not take into account. It is well known that in the condition of normal skin-effect the ratio $\mathcal{X}/\mathcal{R}$ is equal to 1. So, it is natural that the transition of superconductor from critical state to resistive one is accompanied by decrease of the ratio $\mathcal{X}/\mathcal{R}$.

Using the results of surface impedance measurements and the relation (7) it is not difficult to define the dependence $j_c(\mu H)$. These dependences are plotted on Fig.2 for both samples. The parameter μ employed in (7) is taken 0.5.

It is found that the function $j_c(\mu H)$ for all of samples has a good approximation by the power function in a wide range of magnetic field. To our surprise the power exponent proves to be

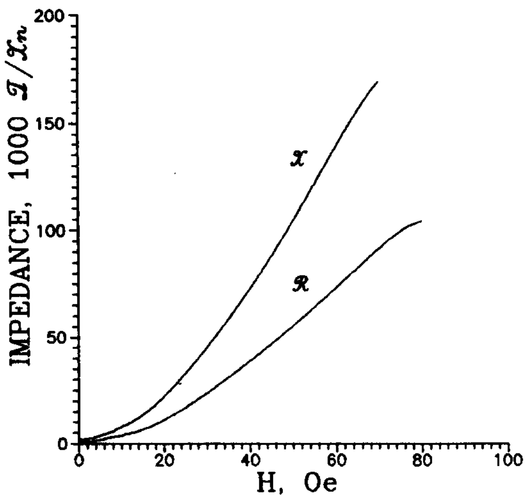

Fig.1 The experimental records of real and imaginary parts of the surface impedance vs external magnetic field for the fine-grained ceramic sample. The amplitude of ac signal h = 1 Oe, the frequency $\omega/2\pi$=1kHz . The normalized constant $\mathcal{X}_n \approx 1.95\cdot10^{-18}$ cgs units.

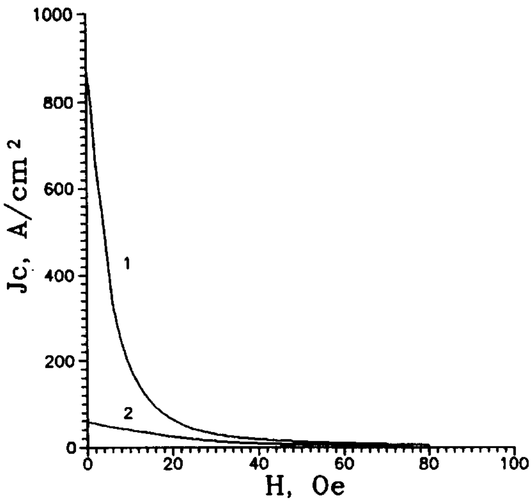

Fig.2 The dependence of critical current density on magnetic field for the fine-grained (1) and coarse-grained (2) samples.

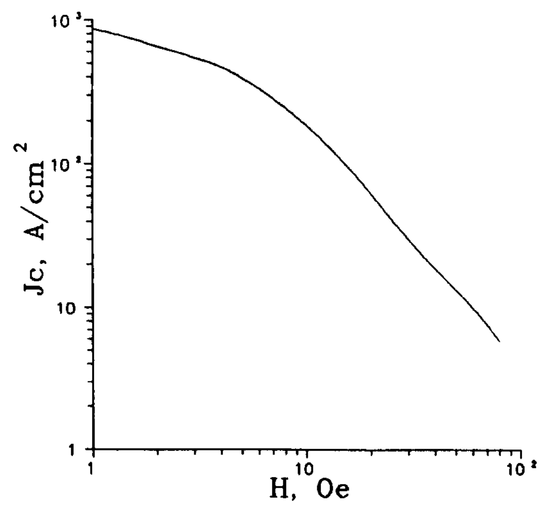

Fig.3 The dependence $j_c(H)$ in double logarithmic scale for the fine-grained sample.

the same and equals -3/2 for different samples. In the case of fine-grained sample

$$j_c(H) = 5.00/H^{3/2} \text{ at } H \geq 5 \text{ Oe}, \quad (12)$$

for coarse-grained sample

$$j_c(H) = 2.05/H^{3/2} \text{ at } H \geq 15 \text{ Oe}, \quad (13)$$

where H and j_c are measured in Oe and A/cm^2 accordingly. In the region of low magnetic fields the relations (12) and (13) become invalid. Really, from Fig.3, demonstrating the dependence $j_c(H)$ for the fine-grained sample in double logarithmic scale, it is clear seen the deviation of the graph from the straight line in the region H < 5 Oe. In order to describe the function $j_c(H)$, taking into account this circumstance, we present other, more complicated fit function $j_c(H)$ which is correct for the all magnitudes of H:

$$j_c=865/[1+(H/H^*)^{7/4}], \; H^* = 4.5 \text{ Oe} \quad (14)$$

for the fine-grained and

$$j_c=55/[1+(H/H^*)^{7/4}], \; H^* = 16.5 \text{ Oe} \quad (15)$$

for the coarse-grained samples.

Let us pay attention to exponents in the relations (14) and (15). In spite of different structure of our sample and great difference in critical current density the exponent value is the same for both types of samples. May be this circumstance is not accidental and it reflects the some unknown objective regularity. However, we have not enough statistical data to maintain an assumption about existence of the universal dependence. One must emphasize that regions of applicability of formulae (12) and (13) for both samples are defined by value H^* in (14) and (15).

Despite the approximations (14) and (15) are more strict, the formulae (12) and (13) are more convenient in practical application. Using (12) and (13) it is possible to find in analytic form the current and field distributions in ceramics.For example,it is not difficult to calculate the value of the full critical current I_c and correlation I_c with radius R of sample without an external field. In the case $j_c = A/B^{3/2}$ the full current has the form

$$I_c = 5\cdot(2\pi A/7)^{2/5}\cdot\mu^{-3/5}\cdot R^{7/5}. \quad (16)$$

This result is in a good agreement with the data of the paper [6], devoted to study the average critical current $\bar{j}_c = I_c/S$ as a function of the cross section S of a sample. In accordance with (16) $\bar{j}_c \sim S^{-0.3}$. The results of measurements[6] correspond to dependence $S^{-1/3}$.

Previously we took the parameter μ= 0.5, considering this choice does not effect on the behaviour of the function $j_c(H)$. However, for the comparison of the critical current (16) with the experimental one we used the value of μ, defined by magnetization curves. The substitution of μ = 0.8 in (16) leads to the result $I_c \approx$ 25 A for the fine-grained sample. For the coarse-grained sample μ= 0.3 and $I_c \approx$ 17.4 A. The results of direct measurement of I_c are 26A and 18A. However, for the practical purposes it is enough to put μ = 0.5, taking into account that parameter μ varies, as a rule, from 0.2 to 0.8 In this case the error in definition of I_c is negligibly small.

4. In conclusion several words about the obtained dependence $j_c(B)$. Independently of ceramics structure the critical current density in the field higher than H^* decreases with field as $B^{-3/2}$ that is much stronger than in Kim-Anderson model[11,12]. This fact is in contradiction with widely disseminated conception that the behaviour of function j_c(B) must coincide with average dependence of critical current I_{cr} of single Josephson junction on magnetic field. At high fields this averaging has to produce $j_c \sim B^{-1}$. This contradiction may be understood if we take into account that at low magnetic field the first oscillations of the function $I_{cr}(B)$ are essential while the dependence $j_c \sim B^{-1}$ would be observed at higher magnetic fields. Unfortunately, we cannot identify the form of function $j_c(B)$ by described above method at higher fields because from the first critical field of the grains $H_{c1} \approx$ 50 Oe magnetic field penetrates into the grains. As a result, the parameter μ in formula (7) becomes a function of magnetic field and increases with H. In these conditions the dependence $Z(H)$ stops to reproduce the function $j_c^{-1}(H)$.

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