THE DYNAMIC SUSCEPTIBILITY OF HTSC-CERAMICS IN A LOW- FREQUENCY RANGE

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On account of physical properties of a ceramic its permeability μ is determined by partial contributions of different parts of a sample. Generally, to calculate μ one can use the methods of accidental medium theory [1]. Further we confine it to the simple approximation, and taking into consideration superconductive granules μ_r and week links between them μ_c contribution to the magnetic susceptibility of a ceramic is written as

$$\mu = (1 - c_r)\mu_c + c_r\mu_r ,$$

where c_r is the relative volume of superconductive granules. As it will be shown, magnetic field H vitally affects μ_c in the range $H \cong H_j$, i.e. the field of Josephson vortices penetration and on μ_r, at $H > H_{c1}$, i.e. the first critical field of the granules.

1. To find partial contributions of Josephson links to both impedance and magnetic susceptibility of a sample it is necessary to solve the dynamic equation for phase difference on a weak link φ [2]. In a low-frequency range $\omega << \sigma$ (here σ is the conductivity of a contact) we can neglect the second derivative over time and write down the equation for φ as follows :

$$\varphi_{xx} - \gamma\varphi_t = \sin\varphi , \tag{1}$$

where scale of length is $\delta_j = \left(\hbar c^2/8\pi edj_c\right)^{1/2}$, of time $t_j = \delta_j/c$, of magnetic field $H_j = \hbar c/2ed\delta_j$, $\gamma = 4\pi\sigma t_j$.

The axis x is directed deep into the contact, the field is exerted along the contact. The boundary condition to equation (1) is:

$$\varphi_x|_{x=0} = H(t) = H_\omega \cos\omega t + H . \tag{2}$$

The surface impedance is determined by the following correlation:

$$\zeta(k,\omega) = \frac{E_t(0)}{H_t(0)} = \frac{\omega}{k_1 + ik_2} . \tag{3}$$

The partial permeability of a link μ, when the depth of penetration k_2^{-1} is less than characteristic dimensions of contact R is

$$\mu \cong \frac{1}{(k_2 - ik_1)R} . \tag{4}$$

In the zero approximation (by parameter $\gamma\omega$) for $H < 2$ the solution of equation (1) is known:

$$\varphi = 4 \text{ arctg} \exp[-Z + Z_0] , \tag{5}$$

where $Z_0(H)$ which is determined from the boundary condition (2) satisfies the equation:

$$\frac{\partial Z_0}{\partial t} = -\frac{\partial H}{\partial t}\frac{1}{H\sqrt{1-(H^2/4)}}. \tag{6}$$

In this approximation the impedance is

$$\zeta = -\frac{i\omega}{\left[1-\frac{H^2(t)}{4}\right]^{1/2}}. \tag{7a}$$

and

$$k_1 = 0, \quad k_2 = \frac{1}{\delta_j}\left[1-\frac{H^2(t)}{4}\right]^{1/2}. \tag{7б}$$

In the first approximation on $\gamma\omega$ we seek the solution of equation (1) in such form:

$$\widetilde{\varphi} = 4 \text{ arctg} \exp\left[-\beta Z + Z_0\right] + \chi, \tag{8}$$

where parameter β is determined from the solvability condition of the equation for χ :

$$\frac{\partial^2\chi}{\partial Z^2} - \cos\widetilde{\varphi}\chi = -(\beta^2-1)\frac{\partial^2\widetilde{\varphi}}{\partial Z^2} + \gamma\frac{\partial\widetilde{\varphi}}{\partial Z}\frac{\partial Z_0}{\partial t} \tag{9}$$

— orthogonality of the fundamental function of left part const/ch $(Z+Z_0)$ to the right.

From this,

$$\beta^2 = 1 + \gamma\frac{8}{H^2(t)}\left[1-\sqrt{1-(H^2(t)/4)}\right]\frac{\partial Z^0}{\partial t} \tag{10}$$

and consequently,

$$\zeta = -\frac{i\omega}{\left[1-\frac{H^2}{4}-\frac{8i\gamma\omega}{H^2}\left(1-\sqrt{1-(H^2/4)}\right)\right]^{1/2}} \tag{11}$$

and, in dimensional units,

$$k_1 + ik_2 = \left[-\frac{1}{\delta^2}\left(1-\frac{H^2}{4H_j^2}\right) + \frac{16i}{\delta_n^2}\frac{H_j^2}{H^2}\left(1-\sqrt{1-(H^2/4H_j^2)}\right)\right]^{1/2}, \tag{12}$$

where the skin layer depth of a normal metal

$$\delta_n = \frac{c}{\sqrt{2\pi\sigma\omega}}.$$

That is to say, in fields H less, than the Josephson field of penetration $2H_j$, Josephson depth of penetration is increased as the field

$\delta_j^* \sim \delta_j\left[1 - \left(H^2/4H_j^2\right)\right]^{-1/2}$, at the same time the effective skin depth is decreased from the value $\delta_n^* = \delta_n$, when $H << 2H_j$, to $\delta^* = \delta_n/\sqrt{2}$, when $H = 2H_j$.

In a magnetic field $H > 2H_j$, in the zero (by the parameter $\gamma\omega$) approximation, the field penetrates into the contact and the solution of equation (1) is expressed through the Jacob ellipse amplitude [2]. In the first approximation on $\gamma\omega$ the equation for correction χ is as follows:

$$\chi_{zz} + \left[\cos\varphi_0(Z) - 1\right]\chi = (-1 + i\gamma\omega)\chi . \qquad (13)$$

Its proper values are expressed by the special function $F(x)$, which is well simulated by:

$$F\left(\frac{H}{H_j}\right) = \begin{cases} 0, & \frac{H}{H_j} << 1 \\ 1, & \frac{H}{H_j} >> 1 \end{cases}$$

Now, it is easy to write the expression featuring the impedance:

$$\zeta = \frac{\omega F(H)}{\sqrt{-i\omega\gamma}} \qquad (14a)$$

and the wave vector k, which determines the susceptibility:

$$k = \frac{1 + i}{\sigma_n F(H)} . \qquad (14б)$$

Thus, magnetic permeability of Josephson links in fields $H > 2H_j$, rushes quickly to (in fields $\sim 2H_j$) its value in a normal metal.

2. To determine susceptibility of ceramics in fields $H > H_{c1}$ we use the vortex–fluid model and we circumscribe penetration of the magnetic field in terms of an effective conductivity σ and the effective depth of penetration λ_s.

In the model of vortices' viscosity flow [3]:

$$\sigma = \sigma_n \frac{H_{c2}}{B} \exp\left[\frac{U_0}{T}\left(1 - \frac{B}{H_{c2}}\right)\right], \qquad (15)$$

here σ_n is the conductivity of ceramics in a normal condition and resolution of the energy of activity $U(B,T)$ was carried out. Consequently,

$$k_1 + ik_2 = \sqrt{-1/\lambda_c^2 + 2i/\lambda_n^2}, \qquad (16)$$

where $\lambda_n^2 = \frac{c^2}{4\pi\sigma\omega}$.

Let's consider two limit cases.

Case 1, $\lambda_s << \lambda_n$, selecting dependence on magnetic field H, for material part μ we get:

$$\mu' = \frac{\alpha}{1 + (b/H^2)e^{-\gamma H}}, \qquad (17)$$

where coefficients α and b depend on parameters of material.

Case II, $\lambda_s > \lambda_n$

$$\mu' = \alpha'\sqrt{H}e^{\gamma H} + b'H^{3/2}e^{3\gamma H}. \tag{18}$$

We have investigated $YBaCu_3O_{7-x}$ samples in tablets, 9 mm diam., 2,5 mm thick, produced by the standard ceramic technology.

Measurements of inductance of flat coil with the sample at 77 K in the magnetic field using a transformer end of alternating current at 1 kHz were carried out. The maximum value of the magnetic field was 2,5 kOe. Samples were cooled in a zero field, after that the field was increased to maximum values, then decreased to zero with following increasing to maximum. At first increasing of the field its induction increases in a monotonous way and at $H < H_{c1}$ is practically of a reversible character. At $H > H_{c1}$, the hysteresis can be observed, which may be explained by the pinning of the field in granules volume. On the following curves $\chi(H)$ the typical minima are observed, which deal with

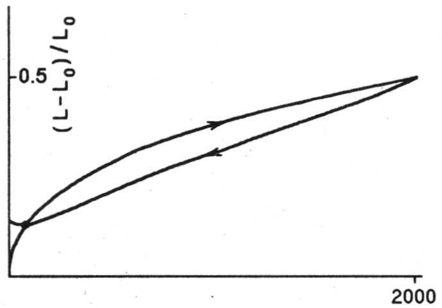

Fig. 1. The dependence of relative inductivity change on magnetic field

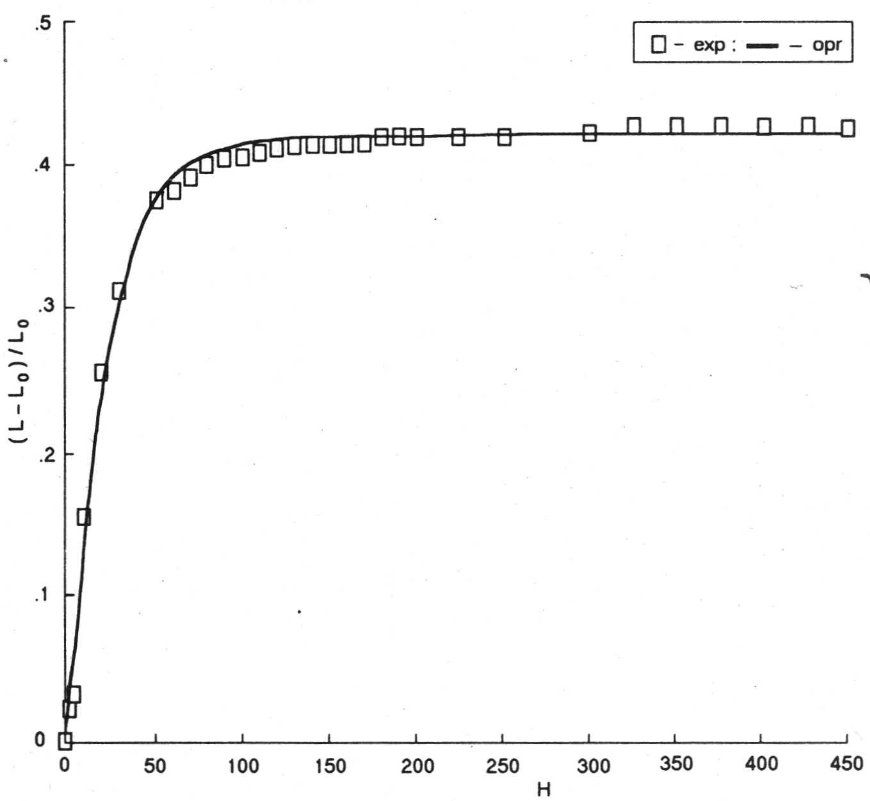

Fig. 2. Change of relative inductivity with a field for sample in which $\lambda_s < \lambda_n$

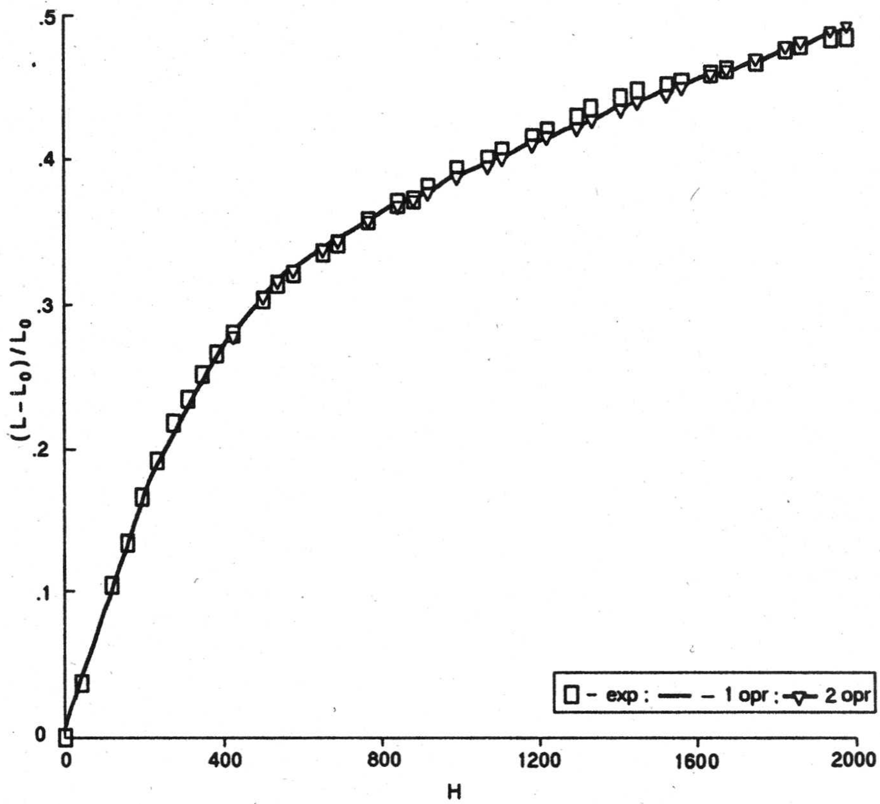

Fig. 3. Change of relative inductivity with a field for sample in which $\lambda_s > \lambda_n$

compensation of external field in week links by the field of vortexes pinning by granules (Fig. 1).

Experimental dependence in first increasing the field is co-ordinated well with our model (Fig. 2 and 3 consequently).

In a field range $H < H_{c1}$ the effect deals with a penetration of field in week links, in fields $H > H_{c1}$ it is permeability determined by viscous vortexes' flow and experimental curves in different limit cases are circumscribed well by (17) or (18).

1. *Zayman J.*, The models of disorder Cambridge University Press, Cambridge (1979), p. 531.
2. *Kulik I. O., Janson I. K.*, Josephson's effect in superconducteing tunnel structures, Nauka, Moskow (1970), p. 272.
3. *Abricosov A. A.*, Basis of metals theory, Nauka, Moskow (1987), p. 519.