Magnetization loop and critical current of porous Bi-based HTSC

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The magnetization of porous Bi$_{1.8}$Pb$_{0.3}$Sr$_2$Ca$_2$Cu$_3$O$_x$ have been investigated. The experimental magnetization hysteretic loops of $M(H)$ were described in the frames of Val’kov – Khrustalev model developed for type II granular superconductors.

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1. INTRODUCTION

High-temperature superconductors (HTSs) having a foam structure [1, 2] is object of fundamental interest connecting with study of transport and magnetic properties in disorder media with fractal dimensions [3]. The high specific surface of foam makes porous HTSs attractive for a practical application. Influence of porosity of HTS on critical current is unclear. Only article [4] concerning this matter can be referred where critical state in superconducting single-crystalline YBa$_2$Cu$_3$O$_7$ foam was considered.

2. EXPERIMENTAL

The standard ceramics method is employed to prepare the porous Bi$_{1.8}$Pb$_{0.3}$Sr$_2$Ca$_2$Cu$_3$O$_x$ (BPSCCO), except the final annealing. The time of synthesis was $\sim$400 h. The decomposition of calcium carbonate realizes during the final annealing stage. The excess pressure of carbon dioxide results in an increase of the material volume. The density $\rho$ of the porous material equals 2.26 g/cm$^3$ (38 % from theoretical one for BPSCCO). The SEM images show that the porous BPSCCO has flakes-like microstructure formed by the chaotic oriented crystallites [2, 3]. The crystallites have thickness $\sim$2 µm and wide $\sim$10-20 µm.

To derive the effect of porosity on magnetic properties, bulk BPSCCO was prepared from the initial porous BPSCCO by the standard technique. For this dense HTS $\rho$ equals 95 % from theoretical one of BPSCCO.

The temperature of zero resistivity ($\leq$ 1 $\mu$Ωm·cm) of porous and dense BPSCCO equals 107 K.

Measurements of magnetic field dependences of magnetization $M(H)$ in fields up to 60 kOe have been performed using the vibrating sample magnetometer with the superconducting solenoid. The specimens have the cylindrical form with height $\sim$4 mm and diameter $\sim$0.7 mm. The mass of sample is 0.0179 g for porous BPSCCO and 0.0264 g for dense BPSCCO. The applied magnetic field was parallel to axis of symmetry of cylinder sample.

3. RESULTS AND DISCUSSION

Figure 1 presents $M(H)$ dependences of porous BPSCCO with low density and dense BPSCCO measured at liquid helium temperature. It is clearly seen that the shape of this dependences is similar, but the absolute value of diamagnetic response is higher in case of porous superconducting material (in 2.4 times in units emu/g and in 1.63 times in units emu).

In the Bean approximation to the critical state [5], the critical current densities can be estimated from the magnetization data as [6] $J_c = 30\Delta M/2R$, where $J_c$ is measured in A/cm$^2$, $\Delta M = M^+ - M^-$ (in emu/cm$^3$) is the width of the magnetization hysteresis loop at a certain magnetic field, $R$ is the radius of cylinder sample (in cm). The obtained zero field values of $J_c$ are 260 kA/cm$^2$ for porous BPSCCO and in 1.63 times smaller, 160 kA/cm$^2$ for dense BPSCCO. However given approach does not take into account granular structure of HTSs. Application of a more appropriate model appears to give some different results. The approach [7] is extension of
the critical state theory for the case of granular bulk HTS. The model [7] allows to draw the hysteretic loops in a broad magnetic field range. This model considers the penetration of magnetic field in the crystallites having form of cylinder. The general expression for performing $M(H)$ calculation in [7] is

$$4\pi M(H) = -H + (1 - P)\mu_n H + \frac{2}{R_0^2} \int_0^\infty \varphi(R) dR \int_0^R r B(r) dr,$$

(1)

where $P$ is the fraction of the superconductor concentrated in the superconducting grains, $\mu_n$ is the magnetic permeability of the intergranular material, $\varphi(R)$ is the distribution density of the superconducting granules, $B(r)$ is the dependence of the magnetic induction on the radius. The main fitting parameter in the model [7] is the average crystallite radius $R$ and critical current density $J_c$, which determines $B(r)$. A new form of dependence of $J_c$ on the magnetic induction $B$ is employed in the model [7] also. This dependence is characterized by the presence of two magnetic induction scales determined by the parameters $B_1$ and $B_0$. These scales demarcate regions with different rates of decrease of $J_c$. The dependence $J_c(B)$ has the following form [7]:

$$J_c(B) = J_c(0) \left[ \frac{1 + Q(B/B_1)}{1 + B/B_1} + \left( \frac{B}{B_0} \right)^\gamma \right]^{-1},$$

(2)

where parameters $Q$ and $\gamma$ determine the rates of variations of $J_c$ for the scales $B_1$ and $B_0$ correspondingly.

Experimental $M(H)$ dependences of a) porous BPSCCO and b) dense BPSCCO - points. Solid lines are results of computer simulation of $M(H)$ dependence using theory [7].

The real crystallites of BPSCCO have a form of plates. Therefore one should to modify the model [7] to consider the penetration of field in the randomly oriented flat crystallites. It will be the task of future investigation. However we do not expect a remarkable difference of magnetization picture.
The pores do not contribute to the magnetization of sample. We accept $P$ equals to the density of material normalized on the theoretical density of BPSCCO. Consequently $P = 0.38$ for porous BPSCCO and $P = 0.95$ for dense BPSCCO. Two parameters are left in the model: $J_c$ and $R$. The experimental magnetization curves are described using the same value of $J_c = 2150 \text{ kA/cm}^2$ and $R = 21 \mu\text{m}$ for porous BPSCCO and $R = 13 \mu\text{m}$ for dense BPSCCO. The solid lines in fig. 1 are results of computer simulation of $M(H)$ dependences in frames of model [7]. A satisfactory agreement between the experimental and theoretical $M(H)$ curves is achieved. If we calculate $M(H)$ using larger $J_c$ for case of porous BPSCCO than dense BPSCCO, the agreement with the experiment becomes worse.

The grain boundaries limit critical current density of polycrystalline HTSs [8, 9, 10]. Especially remarkable influence of grain boundaries are on the critical current density obtained from the transport measurements $j_c$. But roles of grain boundaries in porous HTSs are negligible [2, 4]. However $j_c$ of porous BPSCCO is relatively small. Determination of $j_c$ by using criterion $1 \mu\text{V cm}$ gives $2-100 \text{ A/cm}^2$ at $4.2 \text{ K}$ [3]. These values are smaller than ones for bulk polycrystalline BPSCCO ($\sim 100 \text{ A/cm}^2$). There are supported to be two reasons of decreasing of $j_c$: the reduced effective area of current flowing in porous HTS and the much smaller number of percolation paths in the foam in comparison with the dense HTS. We suppose that the high porosity of HTS does not lead to enhancement of magnetic critical current density $j_c$, instead the broader magnetization curve of porous BPSCCO than one of dense BPSCCO. This suggestion is in contradiction with the prediction of the Bean model. Thus the observed enhancement of the diamagnetic response should be explained by other reasons except increasing of $J_c$, e.g. larger size of the crystallites in porous BPSCCO.

4. CONCLUSION

We investigated and compared the magnetization curves of porous BPSCCO and dense one. The experimental magnetization hysteric loops of $M(H)$ were described in the frames of Val’kov – Khrustalev model [7] developed for type II granular superconductors. The increasing of magnetic critical current density $J_c$ is not found in the porous BPSCCO. Contrary, growth of the porosity is accompanied by decreasing of number of percolation paths that reduces the transport critical current density $j_c$. Discovered enhancement of the diamagnetic response in porous HTSs is very attractive for practical applications, e. g. superconductor bearings and levitators.

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