Influence of strain on transport characteristics of HTSC

A N Moroz, A N Maksimova, V A Kashurnikov and I A Rudnev

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe sh. 31, 115409 Moscow, Russia

Email: moroz.anna@hotmail.com

Abstract. By using the Monte-Carlo method, the dependencies of transport characteristics of a type-II superconductor on the degree of bending strain applied to the sample have been numerically studied. Multiple series of voltage-current characteristics have been acquired for a sample of a high-temperature superconductor for different numbers of strain-induced cracks, as well as various point defects concentrations and different values of external magnetic field. Some peculiarities of the voltage-current characteristics have been detected. Average vortex configurations have been acquired showing that in the points of peculiarities the vortex lattice “freezes” in spaces between cracks. The results for the increasing number of cracks have shown a significant degradation of critical current density.

1. Introduction

Today, type-II superconductors are becoming widely spread. They have successfully found application in various areas, mostly in the form of tapes. However, during the fabrication process the tapes experience different strains, most importantly, bending strains that occur when a tape is wound into coils [1]. Because of this, it is important to study the influence of bending strain on transport characteristics of superconducting materials.

Various studies have been conducted on how bending, compressing, and tensile strains affect the value of critical current density in YBCO films [2-5], and the results indicate that the occurrence of cracks inside the material due to strain leads to the decrease in critical current density.

In this paper we present the results of numerical simulation of influence of cracks and point defects on critical current density of a high-temperature superconductor (HTSC).

2. Model for calculations

All computations have been carried out within the limits of the model of layered HTSC by using the method developed by the authors of [6-7]. The Monte-Carlo method, being based on the theory of probability and mathematical statistics, provides more accurate results for a system with alternating number of particles that take part in different kinds of interactions, and allows to take all the necessary properties of a vortex system into account. The system’s geometry within the limits of this model is shown in Figure 1.

The Gibbs potential for a two-dimensional system of interacting vortices can be described by (1). It is composed of a sum of the vortices’ own energies (2), as well as the energies of vortex-vortex (3), vortex-surface (4), vortex-transport and Meissner current (5), and vortex-defect (6) interactions.

\[ G = N \varepsilon + \frac{1}{2} \sum_{i \neq j} U(r_{ij}) + \sum_{i,j} U_{pn}(r_{ij}) + \sum_{i,j} U_{\text{surf}}(|r_i - r_j|) + \sum_{i} U_{\text{m}}(x_i) \]  

(1)
A $5 \times 5 \ \mu m$ sample of BSCCO superconductor ($\lambda=180 \ \text{nm}$, $\xi=2 \ \text{nm}$, $T_c=84 \ \text{K}$) was chosen for calculations. The degree of strain was simulated by varying the number and length of cracks made in the form of chains of numerous closely spaced point defects with the width of potential well $\sim \xi$, as shown in Figure 2.

\begin{equation}
\varepsilon = \delta \frac{\phi_0^2}{(4\pi \lambda)^2} \left( \ln \frac{\lambda_0}{\xi_0} + 0.52 \right)
\end{equation}

\begin{equation}
U(r_{ij}) = \delta \frac{\phi_0^2}{8\pi^2 \lambda^2} K_0 \left( \frac{r_{ij}}{\lambda} \right)
\end{equation}

\begin{equation}
U_{pn}(r_{ij}) = -\alpha \left( 1 + \frac{r_{ij}}{\xi} \right)^{-1} \exp \left( -\frac{r_{ij}}{2\xi} \right)
\end{equation}

\begin{equation}
U_{\text{surf}}(r_{i} - r_{j}) = \frac{1}{2} \frac{\phi_0^2}{8\pi^2 \lambda^2} K_0 \left( \frac{r_{i} - r_{j}}{\lambda} \right)
\end{equation}

\begin{equation}
U_m(x_i) = \frac{\phi_0}{4\pi} \left( H_0 \left[ \cosh \left( \frac{x_i}{\lambda} \right) \left( \cosh \left( \frac{d l_i}{2\lambda} \right) \right)^{-1} - 1 \right] + H_1 \left[ -\sinh \left( \frac{x_i}{\lambda} \right) \left( \sinh \left( \frac{L}{2\lambda} \right) \right)^{-1} \right] \right) \pm 1
\end{equation}

Figure 1. Geometry of computations. $L=5 \ \mu m$, $\delta=0.27 \ \text{nm}$.

Figure 2. Energy potential of a crack. The depth of potential well $\alpha=0.01 \ \text{eV}$.

Calculations have been carried out for different values of external magnetic field $H$ (0 and 600 Oe). The number of point defects randomly distributed within the sample varied from 100 to 1000. The length of cracks varied from 0.2 to 0.6 of the sample length, and their width equaled that of a single point defect ($\sim \xi$). The number of cracks varied from 0 to 1500.

3. Results

Figure 3 shows a series of voltage-current characteristics for various numbers of cracks from 5 to 20. This sample contained 200 randomly distributed point defects and the external magnetic field value was equaled 600 Oe. It can be seen that the curve for 15 cracks (the curve with upright triangles as markers) has a peculiarity: at some point, while the current density increases, the change in the voltage is very slight.

This happened again for a sample with 500 point defects at the same conditions as above. Only this time, for the case of 12 cracks (the curve with filled circles as markers) the voltage showed a slight decrease.
Figure 3. A series of voltage-current characteristics for a sample with 200 point defects and various numbers of cracks in external magnetic field $H = 600 \text{ Oe}$.

Figure 4. A series of voltage-current characteristics for the same sample as above, only for 500 point defects.

In order to understand the reasons behind such peculiarities, we conducted a detailed study of the behavior of the vortex system, and found out that before (Figure 5 (a)) and after (Figure 5 (c)) the point of voltage step the vortices flow along the cracks. However, in the point of peculiarity (Figure 5 (b)) the vortex flux stops, and the lattice “freezes” in the parts between the cracks. The corresponding voltage-current characteristic is shown in Figure 5 (d). In this case, the sample contained 100 point defects and 21 cracks, and the magnetic field was 600 Oe.

We presume that a particular arrangement of cracks, point defects, and pinned vortices creates an equilibrium-like state that prevents the vortices from moving towards the center of the sample where they can annihilate vortices of the opposite sign (flux-flow).

Figure 6 shows a series of voltage-current field characteristics for a wide range of numbers of cracks from 10 to 700. This time the sample had a fixed number of point defects (500), and the ex-
ternal magnetic field was zero. It can be seen, that the peculiarities occur at much higher numbers of cracks in this case compared to when the magnetic field was nonzero. It can also be said that the increasing number of cracks only led to the increase in critical current density, in other words, the cracks acted as regular pinning centers in this case.

Figure 5. Average vortex lattice configurations for a sample containing 100 point defects and 21 cracks in an external magnetic field $H = 600$ Oe before (a), in (b) and after (c) the point of peculiarities. The corresponding voltage-current characteristic is shown in (d).

However, the increase in the critical current density stopped after a certain point, and $J_c$ started to decrease instead. Figure 7 shows the dependency of critical current density (shown as the field induced by the transport current) on the number of cracks extracted from the previous figure. There is a clear significant decrease in the value of $J_c$ at 830 cracks. We have estimated this number to correspond to a strain with a 15 mm bending radius.
Figure 6. A series of voltage-current field characteristics for a sample containing 500 point defects and various numbers of cracks from 10 to 700, while the external magnetic field equals zero.

Figure 7. The dependency of critical current on bending strain.

4. Conclusion
In this paper, a $5 \times 5 \, \mu m$ sample of high-temperature superconductor has been numerically studied. Voltage-current characteristics have been calculated for different degrees of strain simulated by the number of cracks, as well as for different point defect concentrations and external magnetic field values. Some peculiarities of the voltage-current characteristics (voltage steps) have been detected, and it has been shown that they correspond to a “freezing” of the vortex lattice for small amounts of cracks. A further increase of degree of strain led to a significant decrease in critical current density.

Acknowledgements
The research was done under financial support of RFBR, grant 15-02-02764.
References

[1] Rudnev I, Mareeva A, Mineev N, Pokrovskiy S and Sotnikova A 2014 J. Phys.: Conf. Ser. 507 022029

[2] Cheggour N, Ekin J W, Clickner C C, Verebelyi D T, Thieme C L H, Feenstra R, Goyal A and Paranthaman M 2003 IEEE Trans. Appl. Supercond. 13 3530-33

[3] Sugano M, Osamura K, Prusseit W, Semerad R, Itoh K and Kiyoshi T 2005 Supercond. Sci. Technol. 18 364-8

[4] Shin H S, Dedicatoria M J, Dizon J R C, Ha H S and Oh S S 2009 Phys. C: Supercond. 469 1467-71

[5] Takao T, Koizuka S, Oi K, Ishiyama A, Kato J, Machi T, Nakao K and Shiohara Y 2007 IEEE Trans. Appl. Supercond. 17 3517-9

[6] Kashurnikov V A, Rudnev I A and Zyubin M V 2002 JETP 94 377

[7] Zyubin M V, Rudnev I A and Kashurnikov V A 2003 JETP 96 1065