Field dependence of critical current density in flat superconductor

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Abstract. Surface field of a thin superconductor YBa₂Cu₃O₇₋δ in mixed state is measured by a Hall probe array. To reproduce the measured field profiles, shielding current distributions are determined by numerical iterative calculations without supposing any models for field dependence of critical current density $J_c(B)$. Utilizing the estimated local current density and local magnetic field for $x - y$ coordinates, a field variation of current density is plotted. Though any Model for $J_c(B)$ is not used for numerical calculations, the field variation roughly shows a dependence like Kim model.

1. Introduction
The critical state model, proposed by Bean [1], is very useful for analysis of magnetic properties of type-II superconductor. More recently, it is utilized for study of thin superconductors in perpendicular magnetic field [2]. In these case, it is necessary to consider a field dependence of critical current because of the field profiles in the specimen.

In general, to determine current profiles of shielding currents, a particular model for field dependence of critical current is used [3]. But, the critical current is not determined only by local field. It is also necessary to consider other effects, for example, one by an angle between direction of a local field and a crystal lattice [4, 5]. It is uncertain to know the perfect list of parameters influenced to the critical current in flat superconductors. However, without assuming any models for field dependence of critical current, it is able to determine adequate current profiles numerically. In this work, we derive current profiles without supposing any models for field dependence of critical current density. To converge to adequate profiles, the specimen is divided into ten portions in the numerical calculation and therefore the profiles become rough one. Although detail profiles cannot be derived, phenomenons, not mentioned before, are observed. These do not appear when assuming a certain model for field dependence of critical current.

2. Experiment
In this experiment, we use a c-axis oriented YBa₂Cu₃O₇ epitaxial film having a rectangular shape of size $580 \times 3800 \times 0.8 \mu m^3$ [Figure 1]. To measure the surface field of the sample, a micro Hall probe array is used [6]. The probe is made of GaAs doped with Si and has 10 elements.
Each element has $10 \times 10 \, \mu m^2$ active area. The sample is placed on the probe directly. Therefore a dc field parallel to the c axis of the crystal is measured by the probe. The sample is cooled at zero field and applied a dc field $H$.

Figure 1. Thin superconductor. The length $a$ is 290$\mu$m.

Figure 2 shows a surface field measurement at temperature $T = 20$K. To establish the fully penetrate state, External field $H$ is once set to $H = -5000$ Oe and increasing external field, the surface field is measured. Figure 2 is not one measured at a virgin state. The solid curves show calculated local field $B$.

Figure 2. Profiles of local field $B$ at $T=20$ K. The solid curves show calculated local field $B$ at $20 \, \mu m$ distance from the specimen surface.

Figure 3 shows the screening-current profiles used for calculating $B$ plotted in Figure 2. Each profile is determined with iterative calculating to reproduce the measured field. For the numerical calculation, the specimen is divided to ten portions. Each portion is supposed to have uniform current and then the whole current profiles become bar charts and are not smooth curves. But these current profiles reproduce the measured field quite well in Figure 2.

Figure 3. Profile of calculated current density $J$ at $T = 20$K.

At lower field in Figure 3, the portions near the center of the specimen have larger current densities than the edges. Increasing the external field, the current density of each portion decreases monotonically and the current profiles approximate flat graphs.
In Figure 2, the local field increases according to the distance from the center of the specimen. In spite of the increase of the local field, the calculated current densities do not decrease monotonically in Figure 3. At the edges, the current densities increase slightly and this phenomenon is not predicted by any models for field dependence of critical current. It necessarily drops when using the models.

Values of the local current densities shown in Figure 3 are plotted in Figure 4 as a function of calculated local field shown in Figure 2. At each external field measurement, the field dependency of current density is not clear. But, taking all plotted points into consideration, they are roughly fitted utilized a modified Kim model below.

\[ J(B) = \frac{J_0}{1 + \frac{B}{B_0}} + J_1 \]  

Figure 4. Field variations of current densities at \( T = 20 \text{K} \). A solid line is modified Kim model, a dotdashed line is normal Kim model and a dashed line is exponential model.

Figure 5 shows field variation of current densities at several temperature. Each data set is fitted using Equation (1) and the three parameters used for the fitting, \( B_0 \) and \( J_0 \) and \( J_1 \), are shown in Table 1. In these measurement conditions, regions of temperature and magnetic field, Equation (1) is appropriate.

Figure 5. Field variations of current densities at several temperature. Solid lines are fits using modified Kim model.
Table 1. Parameters used for Figure 5.

| Temperature[K] | $B_0$ [T] | $J_0$ [$10^{10}$ A/m$^2$] | $J_1$ [$10^{10}$ A/m$^2$] |
|----------------|-----------|--------------------------|--------------------------|
| 15             | 0.302     | 30.9                     | 3.35                     |
| 20             | 0.187     | 23.9                     | 4.38                     |
| 30             | 0.160     | 15.8                     | 2.73                     |
| 40             | 0.124     | 11.9                     | 1.74                     |
| 50             | 0.083     | 9.3                      | 1.01                     |

In conclusion, we have measured a surface field of a YBa$_2$Cu$_3$O$_7$ film in perpendicular field. Although any models for field dependence of critical current are not used, the field variations of current density is like Kim model. But calculated current profiles also show influences of uncertain origins except local field.

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