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The time-decaying critical current density of a type-II superconductor and its measuring method

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Abstract

The paper will show that a critical current which has been thought to be defined only in the critical state of a type-II superconductor is able to measure by making use of its time-decaying behavior below onset currents of the resistive state due to flux creep. This is a kind of adiabatic process, in which the measurement of critical currents is done by waiting for a quench which takes place when the persistent current induced in a superconducting sample goes cross the time-decaying critical current and also is a method measuring life of the persistent current in the sample. According to this method, potential barrier models for flux pinning and characteristic parameters about superconductors will be determined.

Keywords: Type-II superconductors; Time-decaying critical current densities; Critical state; Flux creep; Barrier models; Magnetic aftereffect

1. Introduction

Since Anderson predicted in 1962 [1] that time relaxation behavior of the Lorentz-like force parameter in type-II superconductors (hereafter referred to as superconductors) is similar to that of magnetic aftereffect in ferromagnetic materials, a number of studies with respect to relaxation behavior of conventional and high-T_c superconductors have been carried out within the framework of the critical state model [2,3] and the Anderson–Kim theory of flux creep [1,4]. In these experimental studies [5–15], the superconductive state of samples during the experiment has been regarded as the critical state and moreover relaxation behavior of current densities has been thought to obey the well-known logarithmic decay law [9,16], which is a characteristic of the critical current density.

We consider that there exist two kinds of critical current densities in superconductors. One is a critical current density J_{tc} which is explicitly determined by measuring "transport current vs. terminal voltage", *i.e.* I–V characteristics of short superconducting samples [17]. This J_{tc} is one of the basic parameters of their practical applications. Another seems to be a critical current density J_c, which can be implicitly defined only when the critical state model is assumed in an argument related with critical current densities. However, the substance of the critical state or critical current density J_c is not yet grasped in spite of a number of experiments. The critical state has been treated hypothetically and this J_c has been thought to be an unidentified parameter, and J_c is thought to be greater than J_{tc}, which is detected first in measuring I–V characteristics. The objective of the paper is to clear the implicit parameter J_c through investigations with regard to its relaxation behavior $J_c(t)$.

2. Theoretical and experimental backgrounds

The logarithmic decay law for J_c is led from a single kind of barrier model [14] (cf. Appendix), which all pinning centers in a superconducting sample consist of one kind of potential barrier, as follows [16,18]:

$$J_c(t) \cong J_{c0}\left(1 - \frac{kT}{U}\ln\frac{t}{t_0}\right), \tag{1}$$

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where J_{c0} is a critical current density in the absence of flux creep, U a potential well depth for flux pinning, and t_0 a mathematical integration constant within a microscopic time scale [13]. On the other hand, the logarithmic decay law for magnetizations M [10,12,13] is obtained by replacing $J_c(t)$ by $M(t)$ and J_{c0} by M_0 in Eq. (1) from similarity between a current density and a magnetization in electromagnetism. The parameter J_{c0} or the relaxation behavior $J_c(t)$ has been thought not to be determined, because there is no precise critical state since the flux creep continues at any values of current densities J or/and magnetic inductions B in a superconducting sample. Eq. (1), which is called as a pure logarithmic decay [13] curve, is schematically shown as the curve "A" in Fig. 1.

Let us look at in detail the experimental studies [5–15]. In these studies, the decay curves of trapped fluxes [5,6], persistent currents [7,8] and induced diamagnetic currents, *i.e.* remanent magnetizations [9–14] have been investigated for various superconducting materials, sample shapes and experimental conditions, within the measuring time interval 0–5×10^7 s [8]. These curves have been continuously drawn as a curve drawing with one stroke in one measuring run. Taking into account disappearance of superconductivity at J_{tc} or J_c, these curves should be drawn by joining discrete data obtained by a point-by-point measurement in every measuring run. It is easy to judge from an experimental method described in the paper whether those curves are ones drawn by joining discrete data, and to judge whether the measured value is a critical value. The decay quantities, *i.e.* J_c and its substitutes, *e.g.* trapped flux, magnetization and induced current, correspond to their critical values, when loss of superconducting state in a sample is confirmed in a measuring run. However, even if it is a critical value, it is difficult to judge whether it is J_{tc} or J_c. As mentioned later, such judgment will have to depend on a new measuring method, which is able to measure just the critical current density J_c. Therefore, the critical current densities obtained so far by the usual method are thought to be J_{tc}. It turned out from those curves that relaxation behavior did not always obey the pure logarithmic decay law. Namely, the first behavior was a merely linear decay [7,8], the second behavior two components of a linear decay and a pure logarithmic decay [10], the third behavior something like the pure logarithmic decay [11,13,14] and the rest the pure logarithmic decay. Assuming that the integration constant t_0 is of order 10^{-9} s [13,19], the magnitude of decay within the time interval 10^{-9} s to 1 s, *i.e.* the decay rate $(-kT/U)\ \ln t_0$ results in $0.7 \pm 0.1\ \text{s}^{-1}$ from interpolating the decay curves [5,9,12–15] on the graph of a decaying quantity vs. $\ln t$, hence the logarithmic slope kT/U becomes 0.034 ± 0.005. Taking into account that nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) apparatuses are steadily operated at least longer than one year, it seems that a desirable decay rate and logarithmic slope should be less than 10^{-2} of $0.7\ \text{s}^{-1}$ and 0.034, respectively.

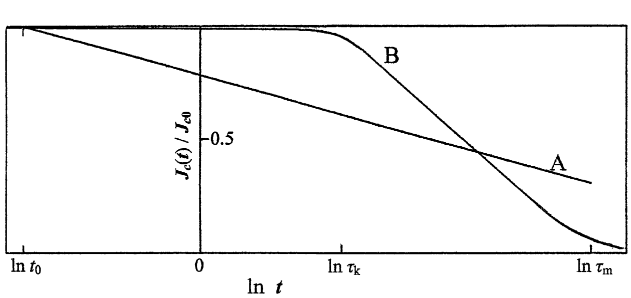

Fig. 1. Schematic graphs of Eq. (1): A and Eq. (5): B.

From the above discussions, the following three points will be concluded: (1) The current densities appeared in the experiments are thought not to be critical current densities. (2) The logarithmic decay law is not universal for relaxation behavior of superconductors. (3) The decay rate at the initial stage is larger than the desirable value by a factor of 10^2. In order to interpret consistently these experimental results, three underlined parts in the following description must be accepted as a fact. As mentioned above, the critical current density J_c, as well as J_{c0}, is an unmeasured parameter, as far as the critical state is not attained all over a sample. The critical state will be attained only through such an adiabatic process as can overcome easily the resistive state due to flux creep and flow phenomena. Of course, J_c has nothing to do with J_{tc}, which need not obey the logarithmic decay law. A decay curve of the critical current density $J_c(t)$ should obey the linear decay law at least within a laboratory time scale in the initial stage of the decay, as it will be mentioned later. The logarithmic decay law was led by introduction of the single kind of barrier model and the Bean model [20]. The rapid drop appeared in the decay curves may be relaxed by exchanging the single kind of barrier model for an advanced barrier model. Introducing the new measuring method making use of the adiabatic process and the advanced barrier model such a multiple kinds of barrier model in magnetic aftereffect of ferromagnetic materials [21] into future investigation, the unsolved phenomena related with the critical current density J_c will be able to observe and to well interpret.

The first-order behavior of magnetic aftereffect observed in a few ferro-magnetic materials can be described by the exponential time law [22]

$$M(t) = M_0\left[1 - \exp\left(-\frac{t}{\tau_0}\right)\right], \tag{2}$$

where M_0 is the initial magnetization and τ_0 a relaxation time characterizing the behavior. Generally, relaxation behavior of magnetic aftereffect observed in most ferromagnetic materials is characterized not by such a sole τ_0 as included in Eq. (2) but by plural τ's with various values within a certain time interval.

Meanwhile, a relaxation time τ in superconductors is related to an effective potential well depth U_{eff} *via* the Arrhenius equation: $\tau = \tau_0\ \exp(U_{eff}/kT)$, in which $\tau_0 \equiv \tau(U_{eff} = 0)$. In the multiple kinds of barrier model, let