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Flux creep in Hg-1201

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Abstract

We report on measurements of the time dependent irreversible magnetization due to flux creep in the high-T_c superconductor $HgBa_2CuO_4$ (Hg-1201). Close attention is paid to the low-field, low-temperature region of the mixed state where flux creep is dominated by the motion of individually pinned flux lines. We have analyzed the relaxational behavior in Hg-1201 in order to specify the nonlinear relationship between activation energy and current density. For the studied temperature region in total, the experimental findings fit in best with predictions given by the collective pinning theory, i.e. the current dependent activation barrier follows a power-law behavior. Towards higher temperatures, however, an uniform description becomes basically questioned by the strong changes in vortex dynamics found earlier in Hg-1201.

Keywords: Hg-based high-T_c superconductors; Flux creep; Pinning

1. Introduction

The mercury based cuprate $HgBa_2CuO_4$ (Hg-1201) becomes superconducting at about 94 K. Quite recently extensive dc and ac magnetization studies [1] revealed a complex vortex dynamics in the mixed state. It turned out that especially the pure phase favors high vortex mobility over large parts of the superconducting phase diagram. Only at temperatures well below the melting transition thermally assisted flux diffusion slows down considerably and enables recording of typical Bean type magnetization hysteresis loops. Even then, however, slow redistribution of flux lines gives rise to gradual changes of the total superconducting dipole moment. This so-called magnetic creep relaxation can be detected properly by means of sensitive long-term magnetization measurements and provides valuable information on pinning mechanism and collective behavior of superconducting vortices at low temperature.

2. Results and discussion

Single-phase $HgBa_2CuO_{4-\delta}$ was synthesized following the procedure described in Ref. [2]. Ceramic samples were prepared afterwards and the dc magnetization investigated.

Magnetic relaxation of superconducting Hg-1201 has been studied at temperatures $T \leqslant 30$ K and for a magnetic field strength up to 3 kG. In this low-temperature, low-field region flux creep is expected to be dominated by motion of individually pinned flux lines. Apart from the fact that temperature and dc magnetic field have a certain effect, in any case the observed relaxation departs from a logarithmic time law. It is commonly accepted that the deviations result from a nonlinear dependence of the mean activation energy U upon current density j. Experimentally, however, they often become clearly visible only at larger time scales. In order to determine the actual relaxation law accurately, thus quite large observation times are usually needed.

An alternative procedure frequently used in literature and originally proposed by Maley et al. [3] is based on the rate equation $\mathrm{d}M/\mathrm{d}t \propto \exp\{-U/\mathrm{k}T\}$ of the irreversible magnetization M which leads to $U = \mathrm{k}T(c - \ln|\mathrm{d}M/\mathrm{d}t|)$.

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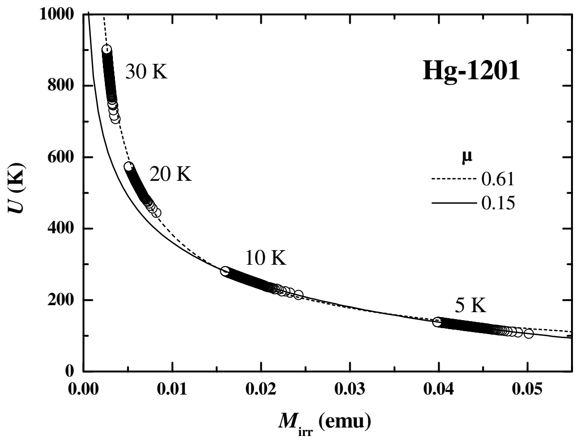

Fig. 1. Dependence of the mean activation energy on the current density and the irreversible magnetization, respectively. A field strength of 1 kG has been applied after cooling the sample in zero field.

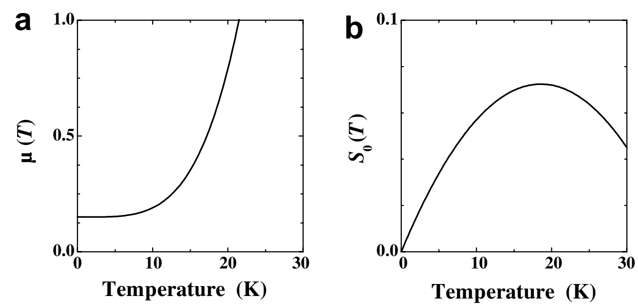

Fig. 2. (a) Temperature dependence of the critical creep relaxation exponent and (b) of the initial logarithmic decay rate averaged over the first 1000 s.

Here c is presumed to be constant and used as fitting parameter assuming a smooth dependence of U vs M as demonstrated in Fig. 1. Since $M \propto j$, at least the functional form of $U(j)$ can be determined this way. In our case, evaluation of the experimental data points to a power law in good agreement with collective pinning theory [4] which generally predicts $U \propto \{(j_c/j)^{\mu} - 1\}$. Here j_c is the critical current density and μ is a critical exponent depending on dimensionality and effective bundle size of the vortex assembly.

At low temperature the power law matches excellently with the experimental findings as is evident from Fig. 1. On enlarging the temperature interval, however, the agreement becomes less accurate and the given ansatz describes the actual behavior just only on average. This arises from the fact that the exponent μ is temperature dependent as well. It is smallest at low temperature but becomes rapidly larger on warming as sketched in panel (a) of Fig. 2.

For $T \leqslant 10$ K we obtain $\mu = 0.15$. This nicely confirms predictions of collective pinning theory for the low-field, low-temperature region, where flux creep is expected to originate from motion of individual vortices. Theoretically, this leads to $\mu = 1/7$ for the three dimensional case.

According to theory, the increase of μ on warming suggests that single-vortex pinning not only becomes affected by thermal fluctuations but also by the interaction between vortices at higher temperatures. In short, our experimental findings give evidence for a crossover from the regime of single-vortex to vortex-bundle pinning.

Although the steady increase of $\mu(T)$ points to gradual changes of an essentially homogenous vortex phase, this idea must be strongly questioned in view of the anomalous temperature dependence of the initial logarithmic creep rate $S_0 \equiv M^{-1}|\mathrm{d}M/\mathrm{d}\ln t|$ presented in panel (b) of Fig. 2. The strong decrease of the normalized creep rate for $T > 20$ K, in particular, suggests heterogenous relaxation associated with distinct pinning regimes which coexist over a certain temperature interval. We assume two pinning regimes, the relaxation rates of which differ much. In consequence, the creep rate represents an average of both a slow and a fast process weighted by the respective volume part. The opposed development of the latter versus temperature then may cause the anomalous behavior of $S_0(T)$ shown above.

On the other hand, fast relaxation processes taking place in parts of the superconductor are hard to detect properly within resolution and time scale recorded by conventional long-term creep measurements. Here, ac-methods are more appropriate to detect magnetization changes associated with rapid flux diffusion. Such investigations provided evidence for fast relaxation processes in Hg-1201 for $T > 20$ K [1].

The crossover region around 20 K therefore separates pinning regimes of different type which becomes obvious also when regarding the field dependent behavior of the creep rate. The field dependence of the low-temperature rate turns out to be rather weak and indicates an activation energy being only marginally influenced, i.e. $U(B) \approx$ const. This, however, is characteristic for single-vortex pinning where interaction between vortices is irrelevant. In contrast, for $T > 20$ K the mean activation energy attributed to fast creep relaxation was found to be strongly dependent on the dc magnetic field in Hg-1201. Such a behavior reflects the important role of vortex–vortex interaction and is therefore highly indicative of a pinning regime where vortex-bundle pinning is dominant.

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