MAGNETIC HYSTERESIS LOOPS AND FLUX CREEP IN SINGLE CRYSTALS OF YBaCuO

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The height of a magnetic hysteresis loop (MHL) of the induced magnetic moment m in high temperature superconductors significantly increases with the rate $\dot{H} = dH/dt$ of change of the external magnetic field H. A linear dependence between m and $\ln|\dot{H}|$ observed on single crystals of YBaCuO is explained on the basis of Anderson's interpretation of the magnetic flux creep in any part of MHL with a constant non-zero slope $\partial m/\partial H$. The increase of m with the sweep rate $\partial m/\partial \ln|\dot{H}|$ is closely related to the relaxation rate $\partial m/\partial \ln(t)$ following from the usual magnetic flux creep. We analyze the temperature and magnetic field dependence of flux creep from MHL recorded at various field rates $\dot{H}$.

INTRODUCTION

The relaxation of the magnetic moment m induced in a superconductor by an external magnetic field H is larger by many orders of magnitude in the high temperature superconductors (HTS) in comparison to the conventional superconductors [1]. As this magnetic moment is generated by the critical current j_c induced in the material [2,3], the study of the magnetic relaxation in HTS is also the study of j_c. In spite of the large difference in the magnitude of the relaxation, the basic mechanism is now mostly believed to be the same for both conventional and HTS, i.e. flux lines in the critical state jump over potential barriers due to thermal activation. This model [4-6] yields the decrease of the magnetic moment m proportional to the logarithm of time t while H is kept constant.

Recently an alternative method for investigation of the magnetic flux creep has been proposed [7]. The increase of the size of the MHL was explained by the effect of magnetic relaxation assuming the logarithmic decrease of m with time in constant H. According to [7] the critical current is a linear function of the logarithm of the rate of the magnetic field sweep in the regions of MHL where the critical current does not depend on H (i.e. where $\partial m/\partial H = 0$).

In this paper we generalize this model to all points of MHL where the slope $\partial m/\partial H$ of MHL is a constant (see Figure 1). We also present new experimental results obtained on YBaCuO single crystals.

MODEL

We always analyze the magnetic moment m induced in samples by large changes of the external magnetic field H when the critical current j_c flows through the whole sample volume, i.e. the sample is in the critical state. The relaxation of m with time t at the temperature T can be described [1,5,7] as

$$m(t) = m(1) - S \ln(t) \ , \qquad (1)$$

where

$$m(1) = m_o \left(1 + (kT/U) \ln(t_o)\right) \ , \quad S = m_o \ (kT/U) \qquad (2)$$

are constants. m_o is the magnetic moment induced in the absence of thermal fluctuations, U is the mean pinning energy of a flux line, and t_o is a characteristic time of the order of 10^{-10} s [1]. m(1) can be interpreted as the value of the magnetic moment 1 second after the start of relaxation.
The rate of the magnetic moment relaxation $[\partial m(t)/\partial t]_{H=const}$ as a function of the actual value of m(t) can be expressed [7] as

$$\left[\frac{\partial m(t)}{\partial t}\right]_{H=const} = - \frac{S}{t} = - S \exp\left(\frac{m(t) - m(1)}{S}\right) \ . \qquad (3)$$

We see from (3) that S can be also interpreted as the rate of relaxation $[\partial m(t)/\partial t]_{H=const}$ at the time t = 1 s.
The effect of continuously changing H was described in [7] using a differential susceptibility χ with the following properties. Neglecting the thermally activated flux creep, a small change of the external magnetic field ΔH will induce the change of the magnetic moment χ ΔH. We only assume that χ can be considered independent on the values of H and m in the vicinity of the analyzed values of H and m. In continuously changing external magnetic field, the sweep rate $\dot{H} = \partial H/\partial t$ will induce the change of the magnetic moment

$$\left[\frac{\partial m}{\partial t}\right]_{\chi} = \chi \ \dot{H} \ , \qquad (4)$$

where the subscript χ indicates that relaxation of m is not considered in this term.
Now we will consider a part of MHL (recorded with constant $\dot{H}$) with the slope $\alpha = \partial m/\partial H$ (see Figure 1). We assume that the relaxation of m while H is sweeping can be described like the relaxation (3) at H = const. The equation describing our situation is

$$\chi \ \dot{H} - S \exp\left((m(t) - m(1))/S\right) = \alpha \ \dot{H} \ , \qquad (5)$$

which gives a similar solution as was analyzed in [7]:

$$m = m(1) - S \ln\left(S/((\chi - \alpha) \ \dot{H})\right) = D + S \ln|\dot{H}| \ , \qquad (6)$$

where

$$D = m(1) + S \ln|(\chi - \alpha)/S| . \qquad (7)$$

We may evaluate the pinning energy U from the relaxation experiments. By eliminating m_o and m(1) from the expressions (2), (6), and (7) we get

$$U = kT \left(\frac{D}{S} + \ln\left|\frac{S}{(\chi - \alpha) \ t_o}\right|\right) \ . \qquad (8)$$

EXPERIMENTAL RESULTS

A single crystal of $YBa_2Cu_3O_{7-y}$ with the shape of a thin plate of area (in the a-b plane) 2.12 mm^2, thickness $h = 30$ μm, and mass 0.401 mg was measured. Magnetic moment m was measured with H along the c-axis by vibrating sample magnetometer [7]. The magnetic moment at small H at 4.2 K was $m = 1.7\times10^{-4}$ Am^2 corresponding to $j_c = 1\times10^{10}$ A/m^2 according to [2].

All values of the magnetic moment m on the slant parts of MHL were corrected to the shift caused by the finite time constant of the magnetometer electronics $t^* = 1.18$ s. Magnetic moment m was evaluated on isothermal MHL at $\mu_0 H = 0.3$ and 1.4 T, see Figure 1.

We took advantage of the symmetry of MHL, $m(H,\dot{H},T) = m(-H,-\dot{H},T)$. The dependence of m on $\ln|\dot{H}|$ was in all cases linear corresponding to (6). This dependence was fitted by

$$m^+ = D^+ + S^+ \ln(\dot{H}) , \qquad m^- = D^- + S^- \ln(-\dot{H}) \tag{9}$$

for $\dot{H} > 0$ and $\dot{H} < 0$, respectively. The values of the slopes $|S^+|$ and $|S^-|$ were very close to each other and we have used only their mean value S in the following evaluation. The non-symmetry of MHL ($|m^+| \neq |m^-|$) is caused by finite value of the reversible magnetic moment $(m^+ + m^-)/2$. We have used the value $D = (m^+ - m^-)/2$ as the relaxing magnetic moment in (6).

The differential susceptibility χ (see (4)) was measured at various H with magnetic field very slowly oscillating with a small amplitude around a given constant value of H (slow ac method). Before each such χ measurement a demagnetization was made by H oscillating around the same constant H value with an amplitude decreasing to zero. The values of χ are between 8.5 and 4×10^{-4} Am^2/T depending on H. The slopes of MHL $\alpha = \partial m/\partial H$ in the analyzed parts of MHL are between 0 and 1.4×10^{-5} Am^2/T, which is always by more than one order of magnitude smaller than the χ values. We have used the values of α in the evaluation according to expressions (6 - 8), but the effect of α is obviously only very small.

We have evaluated the mean pinning energy U according to the expression (8) at several temperatures and external fields. The result is in Figure 2.

DISCUSSION

The values of the differential susceptibility were measured by slow ac method after demagnetization made by H oscillating with an amplitude decreasing to zero. The values of χ obtained in such way, i.e. deep inside MHL under conditions where no flux creep takes place, have been used to describe the dynamic behaviour of the superconductor in the critical state. Therefore it is important to discuss how large is the effect of different χ values on S, D, and U.

We describe in our model the effect of changing H by expression (4) with a constant differential susceptibility χ in the vicinity of the investigated values of m and H. The linear dependence (6) of m on $\ln|\dot{H}|$ is a direct consequence of the logarithmic relaxation (1) at constant H. Such linear dependence is well supported by experimental data. The coefficient S at the $\ln|\dot{H}|$ term (6) does not depend on the value of χ. Parameter D depends on χ, but this dependence is only very slight according to (7).

Similarly the value of the differential susceptibility χ affects only very slightly the resulting value of the pinning energy U. We can conclude that our results are not very sensitive on the exact χ

value.

The pinning energy U evaluated according to (8) is plotted in Figure 2. We have used the characteristic time $t_o = 10^{-10}$ s, [1]. The value of t_o has only a very small effect on the resulting U. The change of t_o by one order of magnitude changes the value of U only by about 10%.

The preliminary results of conventional relaxation (1) at constant H indicate that such rate of relaxation S is smaller than the coefficient S obtained from the hysteresis loops (6). The rate of relaxation $\partial m/\partial t$ at constant H may not be identical with the rate of relaxation at the same values of m and H reached by changing H but this problem should be analyzed in more detail.

The pinning energy U evaluated according to (8) is a steep function of temperature (see Figure 2). Such dependence has been obtained by several authors (see e.g. [8]) from relaxation experiments at constant H. Characterization of the pinning energy by only a single value is obviously only a rough approximation. Real material structure should be described by a statistical distribution of pinning energies.

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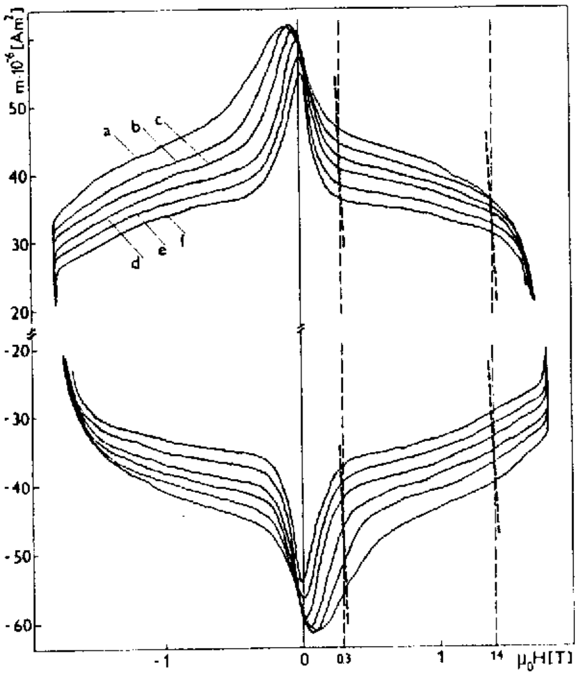

Figure 1:
Magnetic hysteresis loops recorded at T = 11 K at different rates of magnetic field sweep $\mu_0\dot{H} = \mu_0\partial H/\partial t$ at $\mu_0 H$ = 0.3 and 1.4 T. The differential susceptibility χ marked by dashed lines is 7.5 and 4.5×10^{-4} Am^2/T at 0.3 and 1.4 T. The rates the sweep $\mu_0\dot{H}$ are: a) 176 and 96, b) 88 and 48, c) 44 and 24, d) 22 and 12, e) 11 and 6, f) 5.5 and 3 mT/s at $\mu_0 H$ = 0.3 and 1.4 T, respectively.

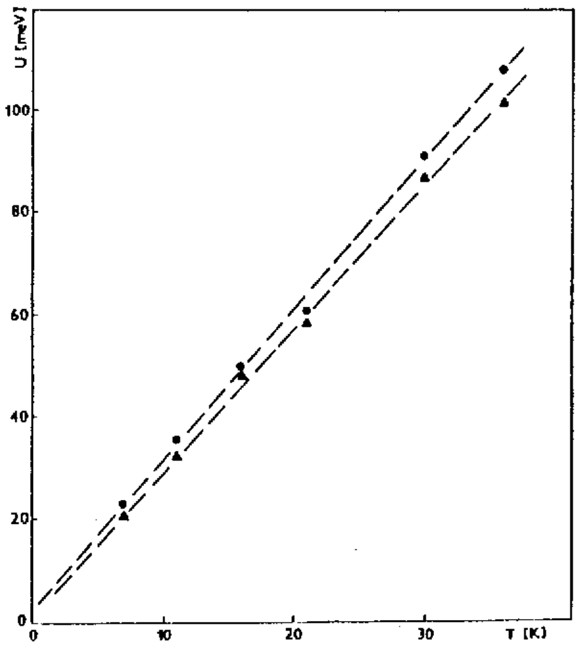

Figure 2:
The pinning energy U evaluated at various temperatures according to (8) at $\mu_0 H$ = 0.3 T, (▲), and 1.4 T, (●).