Correlation between Magnetic Hysteresis and Magnetic Relaxation in YBaCuO Single Crystals

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The dependence of the magnetic moment m obtained from the hysteresis loops on the speed of the magnetic field sweep \( \dot{H} = \frac{dH_{\text{ext}}}{dt} \) is explained on the basis of Anderson's interpretation of the magnetic flux creep. In addition, a phenomenological model is suggested which predicts a linear dependence of m on \( \ln |H| \) with the slope \( \frac{\partial m}{\partial \ln |H|} \), numerically equal to the relaxation rate \( \frac{\partial m}{\partial \ln(t)} \) from the usual magnetic relaxation. Such linear relations between m and \( \ln |H| \) were observed experimentally in single crystals of YBaCuO. Preliminary experiments on the complementary time dependent relaxation of m after a simulated step change of \( H_{\text{ext}} \) gave mostly relaxation rates close to the predicted values. The model here presented also enables one to compare the critical state in the superconductor at a field sweep rate \( \dot{H} \) with the critical state at some time \( t_{\text{eff}} \) after a step change of \( H_{\text{ext}} \). The values of \( \dot{H} \) analyzed in our experiments actually correspond to the critical state at times \( t_{\text{eff}} \) between 0.04 and 4 sec after an imaginary large step change of \( H_{\text{ext}} \).

The magnetic moment induced by the external magnetic field in superconductors is one of the most basic characteristics of the superconducting state. Such induced magnetic moments are in general not stable with time. Recent extensive investigations of the magnetic moment relaxation (creep) in the high temperature superconductors have shown several specific properties. The relaxation of the magnetization is usually reported to be logarithmic with time in both ceramic samples\(^1\)-\(^3\) and single crystals.\(^4\)-\(^8\) Logarithmic decrease of magnetic moments in type II superconductors was first measured by Kim et al.\(^9\) and it is usually explained by the Anderson–Kim flux creep model,\(^10,11\) where flux lines in the critical state jump over potential barriers (with mean energy \( U_0 \)) because of thermal activation.

Because the critical current density \( j_c \) in a superconductor is directly related to its magnetic moment \( m \) through only a geometrical factor as shown by Bean,\(^12,13\) the investigation of the magnetic moment relaxation is
in fact the analysis of the time relaxation of the critical currents in the material.

The logarithmic decrease of \( j_c \) in conventional type II superconductors has been observed in a wide range of pinning strengths, fields, and times, but its magnitude is always very small, e.g. for a given sample over a period of 10 years this decrease amounted to 1%.\(^6\) In contrast, the magnitude of the magnetic moment (critical current) relaxation in the high-temperature superconductors (HTS) is by many orders of magnitude larger (the "giant" flux creep).\(^4,8\) With the exception of high temperatures and high magnetic fields, it also shows the logarithmic time dependence.\(^8\) The basic mechanism of the flux creep in HTS is now believed to be the same as in conventional type II superconductors,\(^10,11\) but the pinning energy \( U_0 \) of flux lines in HTS is much smaller.\(^8\) Small \( U_0 \) along with relatively high temperatures at which the experiments can be performed is believed to be responsible for the large magnitude of flux creep in HTS which has some very important consequences for HTS materials. A time-dependent \( j_c \) is obviously a limiting factor for technical applications. The existence of the irreversibility line\(^4,15\) causes a large range of superconductivity at high magnetic fields and high temperatures, where the magnetic moment is reversible and so the critical currents are close to zero. This irreversibility line also usually determines the Meissner fraction observed after low-field cooling.\(^16\) The magnetic flux creep is directly related to the mechanism of the pinning of flux lines in the superconducting material, and it is possible to evaluate the pinning energy \( U_0 \) of flux lines.\(^8\) The effect of flux creep is also responsible for the shape dependence of the isothermal Bean hysteresis loops on the field sweep speed, as has been qualitatively described by several authors.\(^17,18\) The loops are wider for higher speeds of magnetic field sweep \( \dot{H} = dH_{\text{ext}} / dt \), which corresponds to larger critical currents\(^12,13\) in the material.

In this paper we propose a phenomenological model to explain the dependence of the magnetic moment \( m \) obtained from the Bean hysteresis loops on the speed of the magnetic field sweep \( \dot{H} \). Our experiments, made with single crystals of YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\), are in good agreement with this model which predicts the linear dependence of \( m \) on \( \ln |\dot{H}| \).

The time dependence of the critical current \( j_c(t) \) at constant external magnetic field \( H_{\text{ext}} \) after a large instant step change of \( H_{\text{ext}} \) can be described as \(^19-22\)

\[
j_c(t) = j_{c0} \left( 1 - \frac{kT}{U_0} \ln \left( \frac{t}{t_0} \right) \right)
\]

(1)

where \( j_{c0} \) is the critical current in absence of thermal fluctuations, \( U_0 \) is the mean pinning energy of one flux line, and \( t_0 = 1/\nu_0 \), where \( \nu_0 \) is a characteristic attempt frequency of the order of \( 10^{10} \) Hz. Using the Bean model,\(^12,13\)
we can write down a similar expression for the time dependence of the magnetic moment. Mostly because of comparison with experiments, we will define that the relaxation of the magnetic moment $m$ (critical current $j_c$) is logarithmic in constant $H_{\text{ext}}$ if it follows the time dependence

$$m(t) = A + B \ln(t + C)$$

(2)

where $A$, $B$, and $C$ are constants. Using the proper origin of the time scale ($t = 0$), we can always get the third constant $C$ equal to zero, so in the following we will consider only $C = 0$.

We will express the speed $(\partial m(t)/\partial t)_{H_{\text{ext}} = \text{const}}$ of the magnetic moment relaxation at constant $H_{\text{ext}}$ as a function of the actual value of $m(t)$ by eliminating time $t$ from the derivative of (2) and using (2) to yield

$$\left[ \frac{\partial m(t)}{\partial t} \right]_{H_{\text{ext}} = \text{const}} = \frac{B}{t} = B \exp \left( \frac{A - m(t)}{B} \right)$$

(3)

We will describe the effect of a continuously changing external magnetic field by introducing the differential susceptibility $\chi_0$ with the following properties. Neglecting the thermally activated flux creep, a small change of the external magnetic field $\Delta H_{\text{ext}}$ will induce a change of the magnetic moment $\chi_0 \Delta H_{\text{ext}}$. We only assume that $\chi_0$ can be considered independent of the values of $H_{\text{ext}}$ and $m$ in the vicinity of the analyzed values of $H_{\text{ext}}$ and $m$, but $\chi_0$ may in general depend on $H_{\text{ext}}$. Most of our conclusions are valid even when $\chi_0$ is different from the differential susceptibility measured around the reversible magnetization curve, but we believe that these values are close to each other.

In a continuously changing external magnetic field, the sweep speed $\dot{H} = dH_{\text{ext}}/dt$ will induce the change of the magnetic moment

$$\left[ \frac{\partial m}{\partial t} \right]_{\chi_0} = \chi_0 \dot{H}$$

(4)

where subscript $\chi_0$ indicates that the magnetic moment relaxation is not considered in this term.

To describe the relaxing magnetic moment in a changing $H_{\text{ext}}$, we will assume that the speed of the moment relaxation due to the thermally activated flux creep at any actual value of magnetic moment is given by the expression (3) regardless of how that value of moment has been reached.

The values of the magnetic moment $m$ of the isothermal hysteresis loops (see Fig. 1) recorded with constant $\dot{H}$ are given by a dynamic equilibrium between two effects: (i) the relaxation of the magnetic moment described by (3), and (ii) the change of moment due to $\chi_0$ described by (4). In such parts of the hysteresis loop where the magnetic moment $m$ is
Fig. 1. Bean hysteresis loop measured on a single crystal A at the temperature of 7.5 K with the field parallel to the c axis and at a recording speed $\mu_0|H| = 22$ mT/sec. Both the directly measured magnetic moment $m$ (+y axis) and the critical current calculated according to the Bean model (−y axis) are plotted. The dependence of $m$ on the speed of the field sweep $H = dH_{ext}/dt$ is shown in the right flat part of hysteresis curve along with the differential susceptibility $\chi_0 \approx -4.4 \times 10^{-4}$ A m$^{-2}$/T.

not changing with $H_{ext}$, the time derivative of $m$ should be zero. So we can write, using (3) and (4),

$$O = \left[ \frac{\partial m(t)}{\partial t} \right]_{H_{ext} = \text{const}} + \left[ \frac{\partial m(t)}{\partial t} \right]_{\chi_0} = B \exp \left( \frac{A - m}{B} \right) + \chi_0 \dot{H} \tag{5}$$

which gives the equilibrium value of the magnetic moment on the hysteresis loop

$$m = A + B \ln \left( -\frac{B}{\chi_0 \dot{H}} \right) = A + B \ln \left( t_{eff} \right) \tag{6}$$

where $t_{eff} = -B/\chi_0 \dot{H}$ is the time after an imaginary large-step change of the external magnetic field when the spontaneously relaxing magnetic moment attains the value on hysteresis loop, i.e., we can compare the critical state at the time $t = t_{eff}$ during the spontaneous relaxation and during the field sweep $\dot{H}$.

We can express the magnetic moment $m$ on a flat part of the Bean hysteresis loop as a function of the magnetic field-sweep speed $\dot{H}$ according
to (6) as

\[ m = D - B \ln |\dot{H}|, \quad D = A + B \ln \left| \frac{B}{\chi_0} \right| \quad (7) \]

Notice that the constant at \( \ln |\dot{H}| \) is the same (only with opposite sign), as is the constant at \( \ln(t) \) in (2), used in usual flux relaxation processes.

Single crystals of YBa\(_2\)Cu\(_3\)O\(_{7-\gamma}\) used in our experiments were grown by the pseudo-flux method by slow cooling (2 K/hour) from a gold crucible.\(^{23}\) Sample A with mass 0.401 mg had approximate dimensions 1.6 \( \times \) 0.8 \( \times \) 0.045 mm\(^3\), and sample B had mass 0.376 mg and dimensions 1.8 \( \times \) 1.2 \( \times \) 0.030 mm\(^3\). All measurements discussed in this paper have been made with an external magnetic field parallel to the crystallographic c axis, i.e., along the shortest dimension of our crystals.

The magnetic moment was measured by a vibrating sample magnetometer PAR 155. Bean hysteresis loops were recorded at constant temperature with the external magnetic field smoothly sweeping between values \( \pm 1.9 \) T (Fig. 1). Though the limiting field of our magnet, 1.9 T, is far below the upper critical field \( H_{c2} \), the shape of the hysteresis loop is affected by the finite limiting field only shortly after the change of the field sweep direction (Fig. 1). We performed all measurements in parts of the hysteresis loops in at least 1 T after the change of the sweep direction to have a well-defined critical state\(^{19}\) independent of \( H_{\text{max}} \). We assume that in such a case, the microstructure of the critical state is the same as if we start the field sweep at \( H_{\text{max}} \geq H_{c2} \).

To analyze correctly the effect of the field sweep \( \dot{H} \) on the resulting equilibrium magnetic moment \( m \), it is important to eliminate the effect of the finite time constant of our magnetometer electronics (one second) on the shape of hysteresis loop. We analyzed \( m \) only at \( H_{\text{ext}} \) values where \( m \) is nearly independent of \( H_{\text{ext}} \) and, therefore, the effect of the finite time constant of the electronics is minimized (see Fig. 2).

As the result a very good linear dependence of \( m \) on the logarithm of the field-sweep speed \( \ln |\dot{H}| \) was observed in all analyzed points, in agreement with the theoretical prediction (7) as is illustrated in Fig. 3.

According to our model, the sensitivity of the magnetic moment to the speed of the field sweep \( B' = \frac{\partial m}{\partial \ln |\dot{H}|} \) from (7) should be equal to \( -B = -\frac{\partial m}{\partial \ln(t)} \), where \( B \) is the relaxation rate from usual time-dependent relaxation (2) of the magnetic moment at constant \( H_{\text{ext}} \). We would like to emphasize that we do not need know the actual value of \( \chi_0 \) to evaluate \( B' \) from hysteresis loops recorded at various \( \dot{H} \).

During the time relaxation experiments, the structure of the flux line lattice is changing with time as the critical current and the corresponding magnetic moment are decreasing. The effective time \( t_{\text{eff}} \) defined in (6) enables
Fig. 2. The detailed form of the marked part of Bean's hysteresis loops from Fig. 1 for the different recording speeds $\mu_0|H|$. The vertical line drawn at the field 0.65 T corresponds to the straight line for 7.5 K in Fig. 3.

Fig. 3. The dependence of the magnetic moment $m$ obtained from the Bean hysteresis loops in decreasing magnetic field on the logarithm of the speed $H$ of the magnetic field sweep at three different temperatures measured on single crystal A. (Note the different vertical scales at different temperatures.)
us to compare the flux line structure in the critical state under the magnetic field sweeping with the speed $\dot{H}$ with the structure at the time $t_{\text{eff}}$ after an imaginary large step change of the magnetic field during the spontaneous relaxation. To evaluate $t_{\text{eff}}$, we have used as $\chi_0$ in (6) the value of the differential susceptibility measured deep inside the real hysteresis loop close to the reversible magnetization curve obtained after a "demagnetization"—an application of an ac magnetic field with decreasing amplitude. We found that the values of the field sweep used in our experiments between $-1$ and $-100$ mT/sec correspond to $t_{\text{eff}}$ values between about 0.04 and 4 sec, i.e., we actually analyzed the critical state in our crystals corresponding to the critical state only 0.04 to 4 sec after an imaginary large step change of $H_{\text{ext}}$. This time range is much shorter than can be analyzed by direct measurements of the time-dependent relaxation, where the magnetic moment can be analyzed only after 20 or more seconds.\(^{1-8,24}\)

In summary, we interpret the values of the magnetic moment of the Bean hysteresis loop to be determined by a dynamic equilibrium between two processes: (i) the magnetic flux creep in a constant external magnetic field described by the logarithmic time relaxation (2) and (3); (ii) the change of the magnetic moment in sweeping external field (4) due to the differential susceptibility $\chi_0$, which is assumed to be a constant.

The logarithmic type of the flux creep (2) yields the linear dependence (7) of the magnetic moment on the logarithm of the field sweep speed $\ln|\dot{H}|$ with the slope $B' = \partial m/\partial \ln|\dot{H}|$ equal to $-B = -\partial m/\partial \ln(t)$, where $B$ is the relaxation rate from the usual time-dependent relaxation.

Our experiments show very well the predicted linear dependence of $m$ on $\ln|\dot{H}|$ with the slope $B'$ close to the expected value. By measurement of $m$ on hysteresis loops recorded at various speeds $\dot{H}$, we analyze indirectly the critical state in the superconductor corresponding to the critical state shortly after an imaginary large step change of $H_{\text{ext}}$ (in our case between 0.04 and 4 sec). Our results indicate that the flux creep is logarithmic even at these very short times that cannot be analyzed in experiments directly.

REFERENCES