Journal of Magnetism and Magnetic Materials 101 (1991) 105–106
North-Holland

Flux creep in YBaCuO single crystal observed on hysteresis loops and magnetic moment time relaxation

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Conventional time relaxation of induced magnetic moment m measured at constant B_{ext} on YBaCuO single crystal was compared in the temperature range 7 to 44 K with values of m on magnetic hysteresis loops recorded at different rates of sweep $\dot{B} = dB_{ext}/dt$ (the loop relaxation). The values of m on hysteresis loops are consistent with m values from the conventional relaxation, but they are for larger $\dot{B}$ slightly higher than may be expected from extrapolated data from conventional relaxation. Partial compensation of Lorentz force by viscous forces in moving flux line lattice is suggested as possible explanation of this difference.

The magnetic moment m induced in a superconductor by a change of the external magnetic induction B_{ext} corresponds through only a geometrical factor to the actual value of the induced critical current density j_c [1]. However, j_c is fully determined by distribution of vortex lines through the Maxwell equations. Magnetic moment analysis is therefore a very powerful tool for investigation of both static and dynamic properties of the vortex line lattice.

In a conventional relaxation of the magnetic moment [4] at constant B_{ext} (induced in HTS by a preceding large change of B_{ext}) usually a logarithmic with time dependence of m is observed [2]

$$m(t) = m_1 - S_t \ln(t), \tag{1a}$$

where m_1 and S_t are constants. This behaviour can be well explained by thermally activated flux creep [2,3]. Using a single value of the effective pinning energy U_0, the parameters m_1 and S_t may be interpreted [2] as

$$m_1 = m_0(1 + (kT/U_0) \ln(t_0)); \quad S_t = m_0 kT/U_0, \tag{1b}$$

where $1/t_0$ is the attempt frequency and m_0 is the magnetic moment without relaxation.

The shape of magnetic hysteresis loops (MHL) measured in B_{ext} changing with finite constant sweep rate $\dot{B} = dB_{ext}/dt$ is strongly influenced by the flux creep effect. We will call this effect the loop relaxation [4]. In a model calculation of the size of the hysteresis loops at given constant $\dot{B}$ [5] two effects acting simultaneously were taken into account: (i) the thermally activated flux creep and (ii) the magnetic moment increase due to change of B_{ext} through the differential susceptibility χ. m was found to increase linearly with the logarithm of the sweep rate

$$m(\dot{B}) = D_m + S_B \ln|\dot{B}|, \tag{2}$$

where D_m and S_B are constants. S_t and S_B in (1) and (2), respectively, should be equal [4,5].

This model also enables to label each hysteresis loop with an effective time [5]

$$t_{eff} = \mu_0 S_t/\chi|\dot{B}| \tag{3}$$

which may be interpreted as the time after an imaginary large step change of B_{ext} at which the spontaneously relaxing moment attains the value corresponding to the hysteresis loop measured at sweep rate $\dot{B}$. In this way we can compare the loop relaxation with the conventional relaxation on the same time scale.

The magnetic moment was measured by a vibrating sample magnetometer between 7 and 44 K in a magnet operating between ± 2 T. Results presented in this paper were obtained on a YBaCuO single crystal of thin plate shape of area 2.12 mm^2 (a–b plane), thickness 30 μm and mass 0.401 mg.

Special attention was paid to measure under well defined conditions, especially to avoid overshoot of B_{ext} during stopping the field sweep. Stability of magnetic induction in the B_{ext} = const regime was better than $\pm 6 \times 10^{-5}$. Magnetic induction was recorded simultaneously with magnetic moment to check carefully experimental conditions. The temperature was kept stable during each measurement within approximately ± 0.1 K. Magnetic moment values were numerically corrected for the shift caused by the finite time constant of the magnetometer. The linearity of the field sweep was better than 0.4% in the whole field range.

Magnetic hysteresis loops were measured at five different sweep rates $\dot{B}$ between 0.9 and 90 mT/s. Upper parts of MHL with decreasing B_{ext} measured at 21 K are plotted in fig. 1. Using (2) we can plot the magnetic moment m as a function of t_{eff} (the left side of fig. 2). On the right side of fig. 2 the conventional relaxation of m is shown. Though both ranges of time do not overlap, they may be well considered as two parts of one smooth curve for each temperature and B_{ext} (in fig. 2 only results for $B_{ext} = 0.6$ T are shown for simplicity).

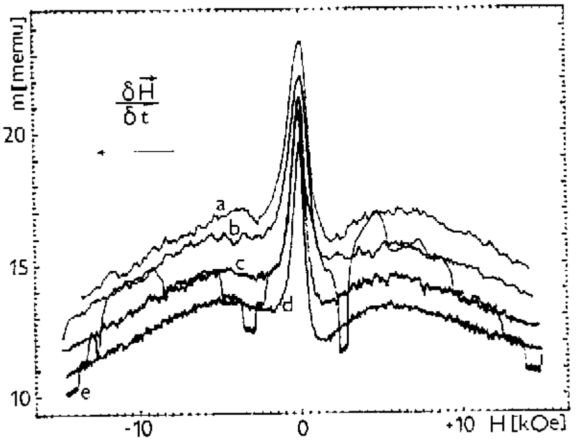

Fig. 1. Upper parts of the hysteresis loops measured at $T = 21$ K with decreasing B_{ext} at five different sweep rates: curves labeled a, b, c, d, e correspond to the rates $\dot{B} = 88.7$, 29.5, 8.8, 2.9 and 0.8 mT/s, respectively.

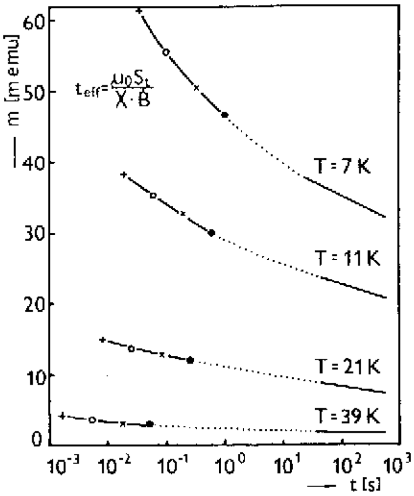

Fig. 2. Comparison of the loop and conventional magnetic moment relaxation in the effective and the real relaxation time, respectively. All data are given for $B_{ext} = 600$ mT. Experimental points described by ○, ×, ○ and + correspond to the sweep rates $\dot{B} = 88.7$, 29.5, 8.8 and 2.9 mT/s, respectively.

Close relation between the loop and conventional relaxation introduced in ref. [5] using the effective time t_{eff} to scale sweep rates $\dot{B}$ is strongly supported by fig. 2. However, the same linear dependence of m on $\ln(t)$ and $\ln(t_{eff})$ was assumed in ref. [5] and obtained theoretically in ref. [4] for both conventional and loop relaxation.

Non-linear increase of m for very small t_{eff} (corresponding to faster sweep rates $\dot{B}$) indicates that either thermally activated relaxation processes at very short times do not follow a simple $\ln(t)$ dependence, or some other mechanism beside the pure thermally activated flux flow may also be important for the distribution of moving flux lines. We suspect viscous forces in the flux line lattice to be responsible for this non-linear increase of m for larger rates of sweep $\dot{B}$. There are two arguments supporting this mechanism: (i) the sign of the difference from straight $\ln(t)$ dependence indicates that the Lorentz force is partly compensated by some other force, which can be of viscous nature, (ii) the difference between the loop relaxation values of m and the straight $\ln(t)$ dependence increases with increasing $\dot{B}$ which is again consistent with the proposed influence of viscous forces.

We would like to thank Dr. J. Pačes and Mrs. J. Smolíková for assistance with experiments and to Dr. L. Kraus for valuable discussions.

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