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 \( B_{\text{ext}} \) 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 \( \dot{B} = dB_{\text{ext}}/dt \) (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 \( B_{\text{ext}} \) 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 \( B_{\text{ext}} \) (induced in HTS by a preceding large change of \( B_{\text{ext}} \)) usually a logarithmic time dependence of \( m \) is observed [2]

\[
m(t) = m_0 - \Delta S \ln(t) \tag{1a}
\]

where \( m_0 \) and \( \Delta S \) 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 \( m_0 \) and \( \Delta S \) may be interpreted [2] as

\[
m_0 = m_0(1 + (kT/U_0) \ln(t_0)) \quad \Delta S = m_0 kT/U_0, \tag{1b}
\]

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 \( B_{\text{ext}} \) changing with finite constant sweep rate \( \dot{B} = dB_{\text{ext}}/dt \) 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 \( B_{\text{ext}} \) through the differential susceptibility \( \chi \). \( m \) was found to increase linearly with the logarithm of the sweep rate

\[
m(\dot{B}) = D_m + S_{\delta} \ln |\dot{B}|. \tag{2}
\]

where \( D_m \) and \( S_{\delta} \) are constants. \( S_{\delta} \) and \( S_{\delta} \) in (1) and (2), respectively, should be equal [4,5].

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

\[
\tau_{\text{eff}} = \mu_0 \Delta S / \chi |\dot{B}| \tag{3}
\]

which may be interpreted as the time after an imaginary large step change of \( B_{\text{ext}} \) 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 \( \pm 2 \) 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 \(\mu\)m and mass 0.401 mg.

Special attention was paid to measure under well defined conditions, especially to avoid overshoot of \( B_{\text{ext}} \) during stopping the field sweep. Stability of magnetic induction in the \( B_{\text{ext}} = \text{const} \) regime was better than \( \pm \times 10^{-5} \). Magnetic induction was recorded simultaneously with magnetic moment to check carefully experimental conditions. The temperature was kept stable during each measurement within approximately \( \pm 0.1 \) 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 \( B_{\text{ext}} \) measured at 21 K are plotted in fig. 1. Using (2) we can plot the magnetic moment \( m \) as a function of \( \tau_{\text{eff}} \) (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 \( B_{\text{ext}} \) (in fig. 2 only results for \( B_{\text{ext}} = 0.6 \) T are shown for simplicity).
Close relation between the loop and conventional relaxation introduced in ref. [5] using the effective time \( t_{\text{eff}} \) to scale sweep rates \( B \) is strongly supported by fig. 2. However, the same linear dependence of \( m \) on \( \ln(t) \) and \( \ln(t_{\text{eff}}) \) 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 \( t_{\text{eff}} \) (corresponding to faster sweep rates \( B \)) 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 \( B \). 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 \( B \) which is again consistent with the proposed influence of viscous forces.

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References