Reduction of flux creep by heat pulses

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We investigated the possibility of reducing the giant flux creep in high-temperature superconductors by temporarily increasing the temperature T above the operating temperature T_0, *after* the critical state is created at T_0. This T increase leads to a *supercritical* state which decays rapidly so that, when T is decreased back to T_0, the superconductor is in the subcritical state. We have found that both the maximum persistent current and the relaxation rate are hysteretic and differ substantially from the corresponding quantities measured after flux annealing. © *1998 American Institute of Physics.* [S0003-6951(98)02001-4]

Many of the potential applications of superconductors demand high current densities with minimum energy dissipation. This in turn requires immobilization of the flux vortices against the driving Lorentz force induced by the flowing current. The pinning of the vortices is especially difficult to achieve in the critical state in which the pinning force and opposing Lorentz force resulting from the induced shielding current almost cancel each other out. Therefore, the vortices can move easily due to thermal activation, mechanical vibrations, or the transport current. A way to reduce the creep rate is to maintain a superconductor in a subcritical state. The decrease of the shielding current density J below the critical current density J_c shifts the equilibrium of forces in favor of pinning.

One way to achieve the subcritical state is presented in Ref. 1 and has been investigated in detail.[2–5] In this method, the critical state is created at an elevated temperature T_A; then the sample is cooled to the operating temperature T_0. As a result, the shielding current density J flowing at T_0 is equal to the critical current density at T_A; since $J_c(T)$ increases with decreasing temperature, $J(T_0) \leqslant J_c(T_A) < J_c(T_0)$. In this way, the relaxation rate of the magnetic moment M is drastically reduced.[2–4] However, the application of this ''flux annealing'' procedure requires advance knowledge of when the magnetic field is about to change in order to raise the temperature above the operating temperature *prior* to that, and keep it elevated until the field is stabilized. There are many applications for which this is impractical or impossible, e.g., when the magnetic field changes frequently or the critical state is generated spontaneously.

We have investigated the possibility of reducing the relaxation rate by keeping the superconductor at an operating temperature T_0 except for a short time when the temperature is raised by a heat pulse *after* the critical state is created at T_0. In this way, the initial shielding current density J equals $J_c(T_0)$. Raising the temperature to $T_0+\Delta T$ results in a *supercritical* state[6] in which $J > J_c(T_0+\Delta T)$. The supercritical current decays rapidly to a certain level $J_X(T_0+\Delta T)$, and when the temperature is lowered back to T_0, the superconductor is in the subcritical state.

We have found that this procedure reduces the relaxation rate substantially, but in a different manner than ''flux annealing.'' Specifically, in contrast to the finding of Refs. 4 and 5, the relaxation of the subcritical state obtained by a heat pulse *is not equivalent* to the relaxation of the critical state after a long time when the current decays to the same value. Second, the temperature dependence of $J_X(T)$ is very different from the typical temperature-dependence of the critical current $J_c(T)$.[1,3] This may indicate the hysteretic nature of the critical state, namely, the values of the maximum persistent current and relaxation rate may depend on the way in which the critical/subcritical state is obtained.

The effect of a temporary increase of temperature on the magnetic relaxation was studied on a single crystal of $Y_{0.87}Pr_{0.13}Ba_2Cu_3O_{7-\delta}$ with critical temperature $T_c \approx 80$ K, grown by a method described elsewhere.[7] The critical state was attained by zero-field cooling the sample from $T=90$ K to an operating temperature T_0, applying a magnetic field of 2 T, and then reducing the applied field to 1 T. The irreversibility temperature of the sample in $H=1$ T is 76.5 K. The magnetic moment induced by the shielding currents was measured with a quantum design SQUID magnetometer using a 3 cm scan length. The decay of the induced moment was monitored over several hours at temperatures 50, 60, and 70 K.

Figure 1 shows a representative set of irreversible magnetic moments $M_{irr}(t)$ measured at 60 K and plotted on a logarithmic time scale. $M_{irr}(t)$ was obtained by subtracting the field-cooled moment from the measured moment.[8] The uppermost curve corresponds to the continuous relaxation at constant temperature. The other eight curves, denoted by the numbers 1–8, illustrate the effect of the heat pulse on the relaxation rate. In all cases, the initial critical state was attained as described above and the first ten measurements of $M_{irr}(t)$ were taken. These initial values of $M_{irr}(t)$ overlap for all nine runs demonstrating that the critical state is completely reproducible.[9] At the moment indicated by the tails of the arrows, the measurement was stopped and the temperature increased to $T_0+\Delta T$. As soon as the temperature was stabilized at this level, it was immediately reduced back to $T_0=60$ K and stabilized again. Then, after waiting three more minutes to insure temperature stability of the sample at T_0, the measurement resumed as indicated by the arrowheads. The duration of the ''heat pulse'' is determined

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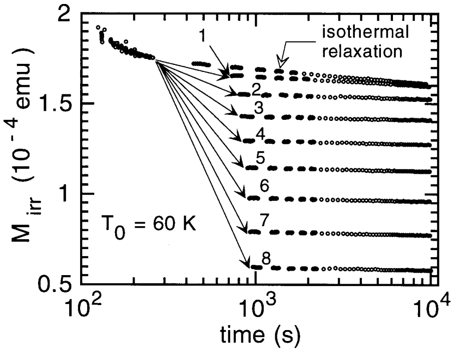

FIG. 1. Relaxation of the irreversible part of the magnetic moment M_{irr} at $T_0=60$ K. The uppermost curve corresponds to isothermal relaxation. The other eight curves illustrate the effect of the temporary increase of temperature at the moment indicated by the tails of the arrows from 60 to 61.25 K (curve 1), 62.5 K (curve 2) etc., up to 70 K (curve 8). The temperature was subsequently returned to 60 K and, after waiting for three more minutes, the measurements were resumed at the moments indicated by the arrowheads.

mostly by the time required to increase and stabilize the temperature without overshooting, and did not exceed 5–7 min. The curves labeled $N=1,2$–8 correspond to progressively larger temperature amplitudes $\Delta T=(1.25\times N)$ K, so that curve 1 corresponds to $\Delta T=1.25$ K, while curve 8 corresponds to $\Delta T=10$ K.

Figure 2(a) is a plot of the starting values M_{irr}^{st} of the irreversible magnetic moment after the heat pulse (at the moment $t_{st}\approx 900$ s, indicated by the arrowheads in Fig. 1) measured at operating temperatures $T_0=50$, 60, and 70 K in a field of 1 T vs $T_0+\Delta T$. In addition, the figure shows the data taken at 70 K in a smaller field $H=0.5$ T. Here $M_{irr}^{st}(T_0+\Delta T)\propto J_X(T_0+\Delta T)$ similar to the flux annealing procedure, where $M_{irr}^{st}\propto J_c(T_A)$. The data corresponding to different T_0 but the same H appear to follow a continuous curve which approximates the shape of $J_X(T)$. The *concave* shape $(d^2J_X/dT^2<0)$ of the temperature dependence of J_X is qualitatively different from the typical *convex* $(d^2J_c/dT^2>0)$ T dependence of the critical current $(J_c\sim\exp\{-\beta_0T\})$.[1,3] In our view, this may indicate that the maximum persistent current at a given temperature and magnetic field is not unique, but depends on the way in which it is induced. Namely, when the induced current increases at a given temperature, the maximum persistent current cannot exceed $J_c(T,H)$.[10] However, when the current approaches its persistent value from above (from the supercritical state due to warming), it may stabilize at the level of $J_X\neq J_c$. The proof of this assertion requires further experiments because M_{irr}^{st} is measured after ≈ 900 s and, during this time, the relaxation due to creep (in addition to the supercritical decay) is not negligible. However, a negative curvature of the T dependence of the magnitude of the magnetic torque hysteresis was also observed in Nb–Ti wires, and was attributed to the supercritical state.[11]

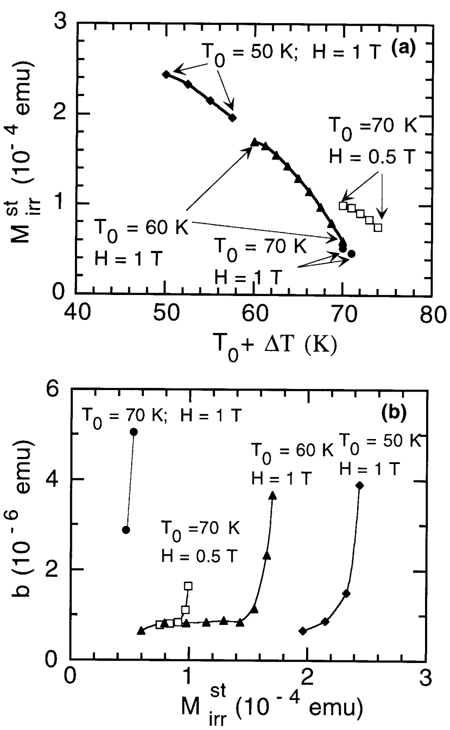

FIG. 2. (a) Plot of the starting values M_{irr}^{st} of the magnetic moment after the heat pulse (indicated by the arrowheads in Fig. 1) vs $T_0+\Delta T$ measured at $T_0=50$, 60, and 70 K in the field of 1 T (filled symbols). The open squares correspond to $T_0=70$ K and $H=0.5$ T. (b) Plot of the relaxation coefficient b, vs M_{irr}^{st} from (a). The symbols are the same as in (a). In both figures, the solid lines are guides to the eye.

The anomalous effect of the heat pulse is also evident in the relaxation rate. Over a limited time span ($t=10^3-10^4$ s), the decay of the magnetic moment after the heat pulse (Fig. 1) can be approximately described by

$$M_{irr}(t)=a-b\ \ln(t/t_0), \tag{1}$$

where a and b are constants, and t_0 is an arbitrary unit of time (hereafter we take $t_0=1$ s). Then, the relaxation rate

$$\frac{dM_{irr}}{dt}=-\frac{b}{t} \tag{2}$$

is determined by the coefficient b which is plotted in Fig. 2(b) as a function of M_{irr}^{st} shown in Fig. 2(a). Initially, the relaxation rate drops substantially with M_{irr}^{st} but, surprisingly, a further decrease of the initial shielding current does not result in a corresponding decrease of the relaxation rate.

It has been suggested that the relaxation of the subcritical state obtained by ''flux annealing'' is equivalent to that of the critical state after a long time t_{offset}, when the current decays isothermally to the same value.[4,5] Based on Eq. (1), the offset time is given by

$$t_{\text{offset}}=t_0\ \exp\left[\frac{a_0-M_{irr}^{st}(\Delta T)}{b_0}\right], \tag{3}$$

where the parameters $a_0=1.95\times10^{-4}$ emu and $b_0=3.7\times10^{-6}$ emu are determined by fitting the isothermal relaxation data for $t>t_{st}$ (Fig. 1) to Eq. (1). Then, the initial relaxation rate of the subcritical state at t_{st} should be

$$\left.\frac{dM_{irr}}{dt}\right|_{t=t_{st}}=-\frac{b_0}{t_{\text{offset}}} \tag{4}$$

or even smaller if the relaxation follows the interpolation formula $M_{irr}\propto[1+\mu b\ \ln(t/\tau)]^{-1/\mu}$.[5] Since M_{irr}^{st} decreases with increasing ΔT [Fig. 2(a)], the offset time increases exponentially and the relaxation rate should decrease exponentially with the amplitude of the heat pulse ΔT [Eqs. (3) and (4)]. However, Fig. 2(b) shows that the relaxation rate actually saturates and remains finite. The measurements at $T = 50$ and 70 K, show the same trend. Quantitatively, the actual initial relaxation rates given by $dM_{irr}/dt = -b/t_{st}$ [the values of b are presented in Fig. 2(b)] are much greater than those predicted by Eq. (4). For example, for $T_0 = 60$ K and $\Delta T = 2.5$ K (Fig. 1, curve 2) with $M_{irr}^{st} = 1.55 \times 10^{-4}$ emu, the calculated offset time using Eq. (3) is $t_{\text{offset}} \approx 5 \times 10^4$ s. The actual relaxation rate $b(\Delta T)/t_{st}$, where $b(\Delta T) \approx 1 \times 10^{-6}$ emu and $t_{st} \approx 900$ s, is a factor of 15 *higher* than b_0/t_{offset}. These results show that the subcritical state obtained by applying heat pulses is not equivalent to the subcritical state when the current decays isothermally to the same value. It is likely that the difference between our results and those of Ref. 4 is due to the hysteretic nature of the persistent current which has also manifested itself in the temperature dependence of $J_X(T)$ [Fig. 2(a)].

Finally, we also found that the subcritical state obtained by a heat pulse is not susceptible to a future temperature rise up to the level of the previous increases. In Ref. 6 it was argued that spontaneous increases of temperature in large magnets are responsible for troublesome decay of the field. We expect that a brief deliberate increase in temperature after the completion of the field cycle may be able to ''inoculate'' the superconductor against turning supercritical spontaneously. The kinetics of the initial decay in the supercritical state is not known. A reasonable assumption is that the time of decay of the supercritical current to the level of persistent current J_X is comparable to the effective attempt time τ for flux motion and may depend on the size and geometry of the sample. Experimental and theoretical estimates of τ indicate values of 10^{-6}–1 s.[12] Raising the temperature of the superconductor for such a short period of time can be achieved most efficiently by current pulses through a *high resistance* electrical conductor in thermal contact with the superconducting cable or film, or by illuminating them with infrared or visual light.

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[9] For all nine runs, the time between the beginning of the relaxation and the first measurement is taken to be 120 s. The relatively small uncertainty in determining when the relaxation actually begins has no effect on the decay rate for times $t > 10^3$ s.
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