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Flux pinning by columnar defects in high-temperature superconducting crystals

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Abstract

Y-Ba-Cu-O:123 and Bi-Sr-Ca-Cu-O:2212 crystals were irradiated with 5.8 GeV Pb ions. The columnar defects, produced by this irradiation are expected to yield the strongest possible pinning energy. Indeed, there is an apparent increase in the width of the magnetization curves. However, the results of magnetic relaxation experiments indicate the energy barrier for flux creep from the columnar defects much smaller than expected pinning energy. This effect is explained in terms of nucleation of vortex loop mechanism of flux creep. The estimate of pinning energy of columnar defect can be obtained from measurement of the angular dependence of the magnetization curves..

1. Introduction

Most applications of high-temperature superconductors (HTSC) are not borne out in reality, mainly because of serious limitations on the magnitude and the stability of the persistent current J_p due to creep or flow of magnetic flux lines. One of the promising approaches in HTSC to enhance J_p is based on introducing damage, in a controlled way, in order to produce reduced-order-parameter regimes in which fluxons are trapped. High energy heavy ions produce columnar defects in the form of amorphous cylindrical tracks of diameter 5-7 nm, embedded in essentially undamaged superconducting matrix. It is expected that this type of columnar defects would yield the strongest possible pinning energy.[1-4]

In recent works we have focused on an experimental study of the flux pinning and creep in HTSC crystals irradiated at G.A.N.I.L. (Caen) with 5.8 GeV Pb ions. We have used two experimental approaches:

(a) Measurement of magnetic relaxations before and after irradiation.[5] The energy barrier for flux creep deduced from detailed analysis of non-logarithmic magnetic relaxations in the framework of the Nelson and Vinokur model[6] are relatively low; e.g. for irradiated $YBa_2Cu_3O_7$ (YBCO) crystals at 82 K the energy barrier is 60 meV and for irradiated Bi-Sr-Ca-Cu-O:2212 (BSCCO) crystal at 60 K it is 5 meV.

(b) Measurements of the angular dependence of the magnetization curves.[7] This approach is based on the idea that the energy of a flux line in a superconducting material decreases with the increase of the angle between the field and the fluxon but, at the same time, there is an energy gain in keeping the fluxon along the columnar defect even if the field is in angle to it.

These two experimental techniques do not yield the same physical parameter, yet they lead to the same conclusion, namely that effective pinning energies are smaller than previously thought.

2. Experimental results.

Magnetization loops and magnetic relaxation were measured, using Local Hall Probe Magnetometer.[8] Miniature InSb Hall probe is placed on the surface of the sample, close to its center, records the stray field H_S of the persistent current circulating in the sample. In the case of a flat sample in a complete critical state this stray field is proportional to the persistent current multiplied by the sample thickness.[9,10]

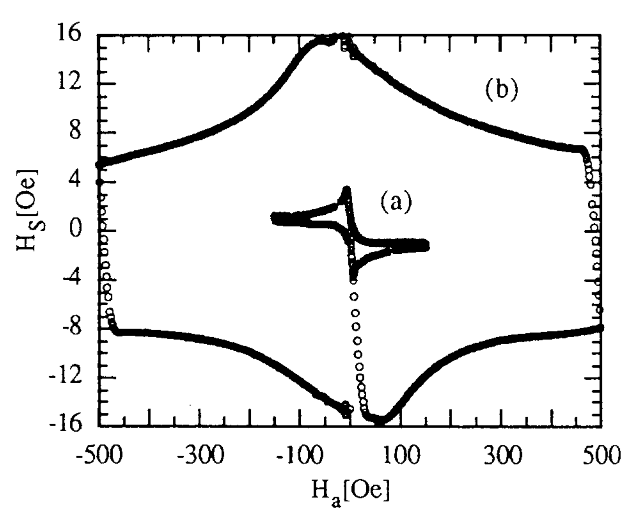

Figure 1. Magnetic hysteresis loops recorded at 90K (a) before and (b) after 5.3 GeV Pb ion irradiation of YBCO crystal (B_Φ=2T).

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A word of warning is appropriate at this point: There may be other sources for hysteresis loop rather than bulk pinning. In particular, it has recently been demonstrated[11] that Bean-Livingston surface barriers are the main origin for the opening of the magnetization loop in HTSC crystals at high temperatures where bulk pinning is virtually negligible. In this case, the width of the loop does **not** reflect the persistent bulk currents.

Typical magnetization loops, recorded on $YBa_2Cu_3O_7$ crystals before and after Pb ion irradiation, are presented in Fig. 1. The total fluence in this case is 10^{11} ions/cm^2, corresponding to a matching field of B_Φ=2T. (For B_Φ the distance between the fluxons matches the distance between the defects). As explained above, the dramatic increase of the width of the loop should not be used for the estimation of the enhancement of critical current. At the measuring temperature (90 K) the unirradiated sample may be considered as reversible. The persistent current in the irradiated sample is almost entirely sustained by the columnar defects.

Another manifestation of the pinning from columnar defects is the enhancement of thermoremanence presented in Fig. 2. The enhancement of the thermoremanence is more dramatic at high temperatures, practically above 70K.

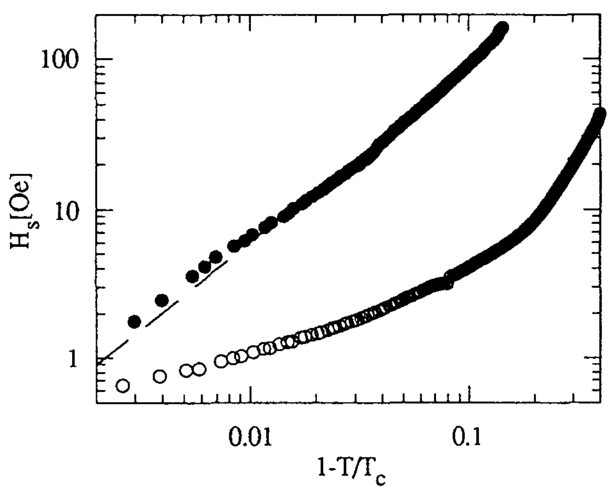

Figure 2. Termoremanence recorded after field-cooling on $YBa_2Cu_3O_7$ sample before (open circles) and after 5.3 GeV Pb ion irradiation (full circles).

In the following we focus on magnetic relaxation recorded at high temperatures. Typical data, recorded at 88K for YBCO crystals irradiated with total fluence of 10^{10} and 10^{11} ions/cm^2, (B_Φ=0.2T and 2T), respectively, are presented in Fig. 3.

The procedure used to start the relaxation consisted of cooling the sample in field followed by positive or negative pulsing of the field to trigger relaxation for flux expulsion or flux penetration, respectively[5]. For clarity we present here data for flux penetration only; data for flux expulsion are essentially the same. As can be seen in Fig. 3, the magnetic decay is slightly non-logarithmic with the slope decreasing with time.

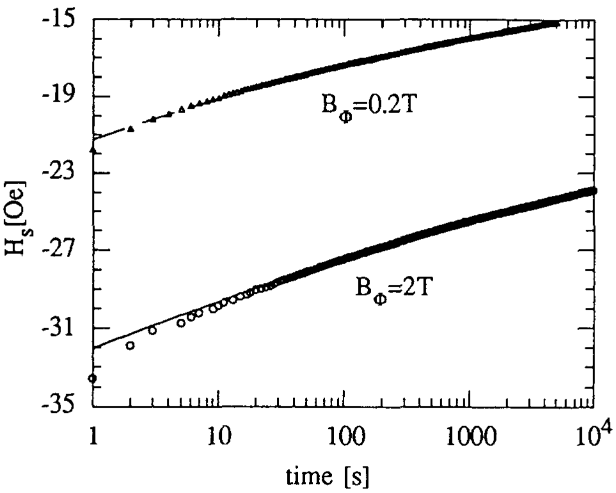

Figure 3. Magnetic relaxations recorded at 88K and 300 Oe on two $YBa_2Cu_3O_7$ samples irradiated with 5.3 GeV ions.

More insight into the character of the magnetic decay can be obtained by analyzing the logarithmic derivative $S=-\frac{\partial \ln H_s}{\partial \ln t}$. By plotting $\frac{1}{S}$ vs. time (Fig. 4) we demonstrate an increase with time of U ($U\propto\frac{1}{S}$), the effective barrier for flux creep. Since the persistent current J_p is decreasing with time, it is also apparent from Fig. 4 that U decreases with J_p. The values of S were calculated numerically over the interval of 1 decade in the time scale.

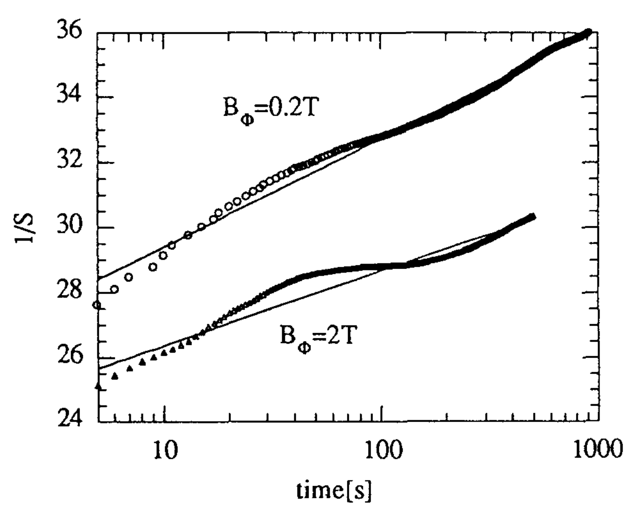

Figure 4. Evolution with time of the inverse of the normalized logarithmic slope calculated from the magnetic decays of Fig. 3.

The BSCCO crystals irradiated with 5.3 GeV Pb ions exhibit drastic up-ward shift of the irreversibility line (identified by the onset of the 3^{rd} harmonic component in magnetic susceptibility) and enhancement of the magnetic irreversibility[12].

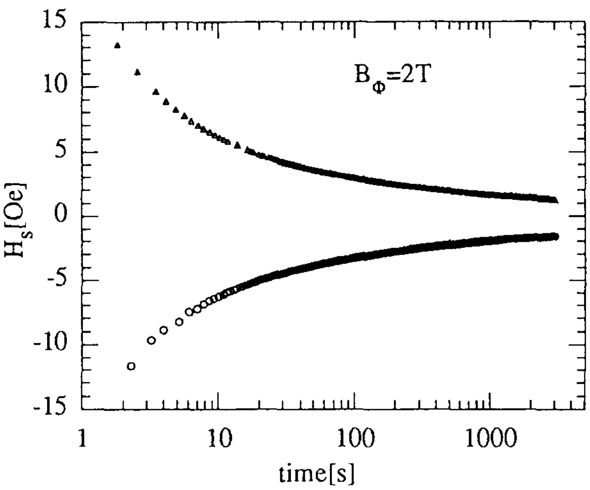

Figure 5. Magnetic decay recorded at 60 K at 300 Oe on BSCCO-2212 crystal irradiated with 5.3 GeV Pb ions. Fluence: 10^{11} ion/cm^2. Two records correspond to flux leaving (upper curve) and flux penetrating (lower curve) relaxations.

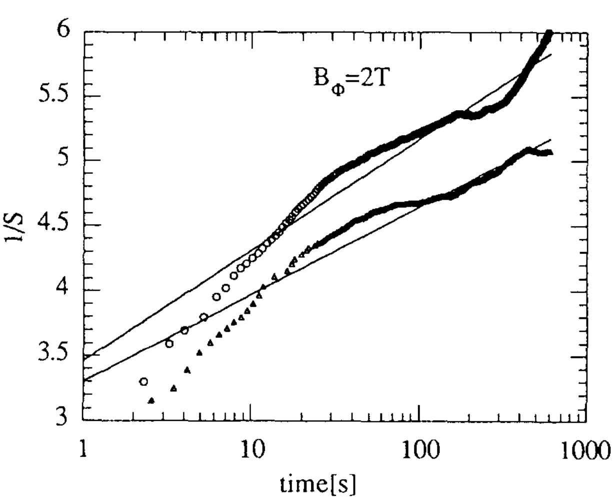

Figure 6. Evolution with time of $\frac{1}{S}$ calculated from the magnetic decay data of Fig. 5. Both processes of flux leaving and flux penetrating relaxation lead to the similar increases of $\frac{1}{S}$ with time.

In Fig. 5 we describe magnetic relaxations at 60 K and 300 Oe for the BSCCO crystal irradiated with fluence of 10^{11} ions/cm^2, (B_Φ=2T). For the unirradiated crystal these temperature and field values represent a point above the irreversibility line. The relaxation process induces a change of more than one order of magnitude in the magnetization and it is strongly non-logarithmic. The plot of $\frac{1}{S}$ vs. time, deduced from the data of Fig. 5, is presented in Fig. 6. This figure demonstrates clearly the growth of the effective barrier U with the decrease of the persistent current.

3. Discussion

Collective pinning by weak pinning centers in unirradiated samples[13] induce an increase of U for decreasing J_p. A similar behaviour is expected[6] for strong flux pinning by columnar defects. In both cases vortex creep is controlled by nucleation of vortex loop and the relevant creep barriers diverge as $U=U_c(\frac{J_1}{J_p})^\mu$ leading to a current-voltage characteristic of the form:

$$E \propto \exp[-\frac{U_c}{T}(\frac{J_1}{J})^\mu] \tag{1}$$

The effective barrier for flux creep corresponds to the formation of the critical nucleus or critical vortex loop. The size of the critical loop, L is determined by the competition between the Lorentz force driving the vortex away and the pinning force binding the vortex to linear defects The size of the critical loop grows as $L\propto\frac{1}{J_p}$, and so does the nucleation energy. At sufficiently large currents, when creep is determined by the thermal activation of the vortex from the single rod, one expects μ=1. At smaller current, when creep occurs via thermally activated vortex hop from one rod to another, in a process analogous to variable range hopping conductivity in semiconductors, one expects $\mu=\frac{1}{3}$ provided that the concentration of vortex lines is low enough[6].

Magnetization decay in this model is given by an interpolation formula:

$$M(t) = \frac{M_o}{[1+\frac{\mu T}{U_c}\ln(\frac{t}{t_o})]^{1/\mu}} \tag{2}$$

and the creep rate slope from (2) is:

$$\frac{1}{S} = \frac{U_c}{T} + \mu\ln(\frac{t}{t_o}) \tag{3}$$

The magnetic decays reported above for YBCO and BSCCO irradiated crystals fit the prediction of the nucleation creep model of Nelson and Vinokur.[6] The increase of $\frac{1}{S}$ with time is almost logarithmic providing good determination of the exponent μ. For the YBCO crystals μ equals 1.45 and 1 for matching fields of 0.2T and 2T, respectively. These high values of μ rules out an alternative explanation of non-logarithmic magnetic decay in the framework of vortex-glass model[14]. The somewhat high value of μ obtained for sample with columnar defect density corresponding to 0.2T matching field can be viewed as a result of departure from local elasticity description of vortex loop nucleation process. In this sample, at low current because of large track-to-track distance and large loop size, the vortex-vortex interactions should be taken into account; this leads to some modification of the value of the exponent μ. The determination of the energy barrier U_c can not be done unambiguously. The intercept of $\frac{1}{S}$ vs. time variation at 1s, $\frac{U_c}{T} + \mu \ln(t_o)$ contains the effective attempt time t_o, which in this description is a macroscopic parameter.[15] With an estimate for t_o of 10^{-5} - 10^{-6} s, we obtain the value of U_c of the order of 60meV.

The slope of the logarithmic increase of $\frac{1}{S}$ in BSCCO-2212 containing columnar defects (see Fig. 6) yields a value of μ=0.33±0.04 which corresponds to low J_p regime, equivalent to a variable range hoping in doped semiconductors. To estimate U_c we take the lowest realistic estimate for an effective attempt time $t_o=10^{-3}$ s. From the intercept of $\frac{1}{S}$ vs; time at 1s we obtain $\frac{U_c}{kT} \approx 1$ or $U_c \approx 5$ meV.

The routine determinations of flux creep barrier from logarithmic slope of relaxation process in the typical time window of 100-1000s leads to essentially wrong result. As pointed out by Malozemoff and Fisher[16] in the collective pinning regime at high temperature, the logarithmic slope reflects mainly the product of the exponent μ and $\ln(\frac{t}{t_o})$. The same argumentation can be applied to nucleation creep from columnar defects of concern here.

These very low estimates for U_c in the presence for columnar defects in YBCO and BSCCO crystals, point out paradoxal situation of the strong pinning picture with very low barrier for flux creep. The low line tension in highly anisotropic superconductors allows nucleation of vortex loop from pinned vortex line at low energetic cost and seems to be the main limiting factor for stability of flux gradients.

A similar conclusion has recently been drawn from measurements of the angular dependence of the magnetization curves for irradiated YBCO crystals. The magnetization curves confirm an anisotropic enhancement of J_p, namely the width of the loop is the largest for fields oriented along the defects. However, a sharp crossover to isotropic behavior is observed in the low-field limit. In this limit the magnetic data is **independent** of the direction of the field, indicating reorientation of the flux lines along the direction of the defects. To understand this phenomenon, which we coined 'flux flop', we note that the diameter of the defect is larger than the coherence length. As a result, the energy of the fluxon in the defect is significantly larger than the energy of a "usual" Abrikosov vortex. In other words, the relative energy gain for a fluxon along a columnar defect is much larger than the usual gain in the core condensation energy for point defects. Thus, there is an energy gain for a fluxon to be oriented along the defect. However, in the high field limit the Gibbs free energy is dominated by the direction of H. and the fluxons point in this direction. When the field is decreased the flux lines are gradually aligned towards the c axis in order to minimize the length of the flux line. Finally, at low enough fields there is an energy gain for the fluxons to "jump" into the defects. We observe jumps as big as 45°. We may thus estimate the energy of the defect by comparing it to the Gibbs free energy. We conclude that the energy gain is only order of magnitude larger than that of a fluxon trapped in a point bulk defect.

In conclusion, the huge enhancement of observed magnetic irrevrsibility after introduction of columnar defects is essentialy due to the rapid growth of effective barrier for flux creep with decreasing persistent current.

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