Comparison of superconducting flux pinning due to ion irradiation and fishtail effects

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(Received 10 October 1995)

Heavy-ion irradiation experiments have been carried out for single crystals of $YBa_2Cu_4O_8$ in order to compare the magnetic-field dependence of the flux pinning for damage channels with the intrinsic "fishtail" pinning that occurs in this material before irradiation. The two pinning effects seem to be additive in that irradiation increases the hysteresis at all fields and the fishtail hump persists in the irradiated samples with roughly the same magnitude as before the damage channels are produced. For irradiated samples, there are two regions where pinning rises with increasing field, one near zero field due to a matching effect of the defect density with the vortex lattice spacing and a second at the same field as the original fishtail. Both effects appear in the same sample in different magnetic-field ranges.

I. INTRODUCTION

Columnar defects in the form of amorphous tracks can be produced in high temperature superconducting crystals by heavy-ion irradiation. Flux pinning by this type of artificial defect dramatically enhances critical current density, shifts irreversibility line, and depresses magnetic relaxation.[1–4] Single crystals of $Y_1Ba_2Cu_4O_8$ have proven to be an excellent material to study flux pinning because the virgin crystal has very small bulk pinning and various defects can be added systematically to test models. Previously, it was reported[5] that these crystals have magnetization hysteresis loops with the classic shape predicted by Clem for Bean-Livingston surface barrier pinning.[6,7] As shown by the inset in Fig. 1 for example, the magnetization at 35 K rises from zero along a Meissner line to a flux entry field at about 50 mT. At higher fields, the magnetization follows an Abrikosov shape out to about 1 T as vortices flood over the barrier and fill the sample interior with a flux-line lattice. If the field is then decreased, the magnetization again follows the Meissner slope until the field is zero. At this point, the Meissner surface currents that normally push the vortices into the sample are zero and the only force on the vortices near the surface are the image forces and the vortices flood out to make the magnetic induction equal to the applied field, $B = H$, or magnetization, $M = 0$. Finally, at fields below 400 mT bulk pinning increases, and the magnetization goes positive at lower fields as illustrated on the inset of Fig. 1. At fields above 1 T, fishtail pinning turns on to give the data reported previously.[5]

The goal of this work is to start with this well-characterized sample that exhibits both the fishtail effect plus surface barrier pinning and add an additional pinning mechanism caused by damage channels along the c axis through the entire sample created by heavy-ion irradiation. By adding this third pinning mechanism, it is possible to learn whether the effects of separate mechanisms have a simple additive effect on J_c and it will be possible to look for a matching effect between the damage tracks and the vortex lines inde-

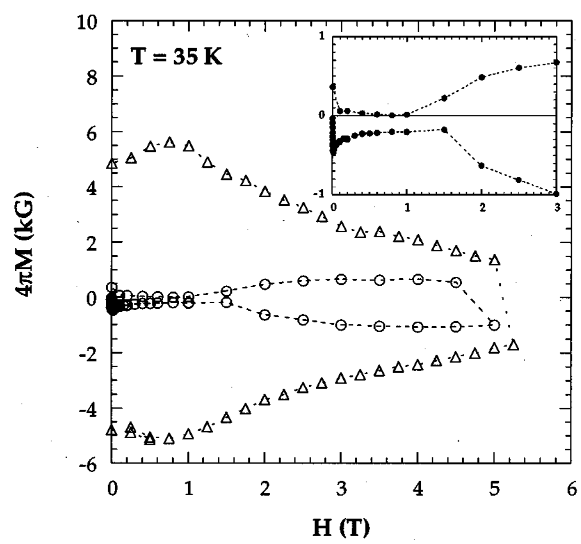

FIG. 1. Magnetic hysteresis loops at 35 K for the as-grown crystal (the open circle) and the irradiated crystal with a 2 T ion dose along the c axis (the open triangle). The applied fields are parallel to the c axis. The dashed lines are the guide to the eyes. Inset: Hysteresis loop at 35 K for the as-grown crystal with a feature of the surface barrier at low field ($H<$ 1 T) and fishtail at high field ($H>$ 1 T).

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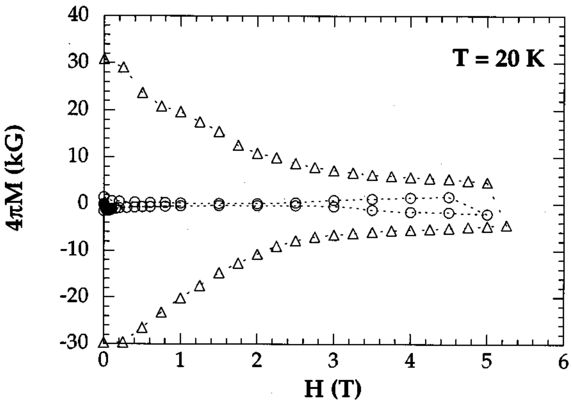

FIG. 2. Magnetic hysteresis loops at 20 K for the as-grown crystal before irradiation (the open circle) and the irradiated crystal with a 2 T ion dose along the *c* axis (the open triangle). The applied fields are parallel to the *c* axis. The dashed lines are guide to the eyes.

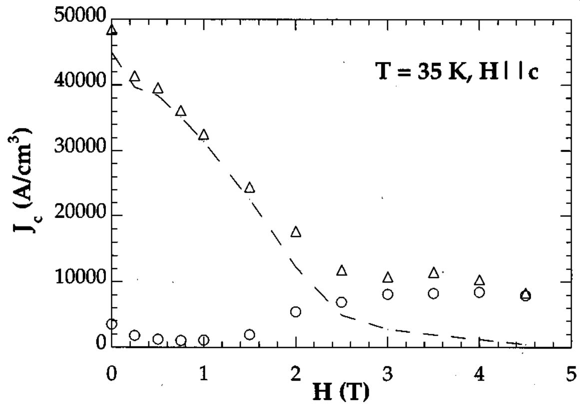

FIG. 3. Critical current density J_c, in the *a* plane, at 35 K for the as-grown crystal (the open circle), the irradiated crystal with a 1 T ion dose along the *c* axis (the open triangle), and the difference between them (dashed line).

pendent of the fishtail effect seen in the starting material. The magnitude of the fishtail-type hysteresis induced for several crystals from the same batch were the same within a factor of 2 for the samples used here.

II. EXPERIMENTAL TECHNIQUE

For the irradiation samples, a single crystal was broken in two and both halves were polished to a thickness of 0.02 mm, a value thin enough to allow the damage tracks to traverse the entire thickness of the sample. Irradiation of the sample was done at the Atlas Accelerator at Argonne National Laboratory with a beam of 605 MeV Xe ions having charge of +26 times the charge of a proton and a density of 10^7 ions/cm^2 s. In this work we refer to the magnitude of the irradiation dose in terms of the matching magnetic field where the average spacing between damage tracks is the same as the spacing between vortices at a given field. Irradiation to a matching field of 1 T means that the average spacing between damage tracks ~ 40 nm, is the same as the spacing of vortices at 1 T. The irradiation are made with the ion-beam line parallel to the *c* axis for all samples. In other respects the experimental details are the same as reported earlier.[5]

Magnetization data are measured using a commercial superconducting quantum interference device (SQUID) magnetometer with applied fields up to 5 T at various temperatures. Scan lengths of 3 cm are used to ensure that the field on the sample remains constant as the sample is driven between the SQUID coils. The magnetic fields are applied parallel to the *c* axis of all samples. To obtain critical current density, J_c, measurements, the difference in the increasing and decreasing field magnetization values is parametrized in terms of the critical current density values in the *ab* plane, using the Bean model.[8,9]

Transmission electron microscopy (TEM) work on a sample irradiated to a matching field of 0.5 T reveals that the irradiation tracks are columnar defects with a diameter of 4–5 nm, consistent with earlier work.[1] The column diameter depends only upon the energy of the ion beam on the targets. The defects are randomly spaced and have an average distance of the nearest neighbor that depends upon irradiation time. As is customary, the density of defects is expressed in terms of a matching field, defined to be the magnetic field at which the area density of vortices is the same as the area density of columnar defects. The average spacing between defects then goes as the square root of the matching field.

III. RESULTS AND DISCUSSION

The introduction of damage channels has the largest effect on the hysteresis loops in the region of 1–2 T where the spacing of the vortices matches the spacing of the damage channels as shown in Fig. 1. A blowup of the data for the unirradiated sample reported earlier[5] is sketched as an inset in Fig. 1, and the actual data are shown by the open circles. For a matching field of 2 T and a temperature of 35 K, the magnitude of the hysteresis increases as the field increases from 0 to 0.8 T and then decreases at higher fields. In the region of 3–4 T, there is a slight flattening out as though the fishtail effect shown in the unirradiated sample were still present in the irradiated sample. The peak in the magnetization at 0.8 T associated with the matching field comes at less than half the nominal matching field of 2 T.

At lower temperatures, as shown for the 20 K data in Fig. 2, the magnetization and hysteresis falls monotonically from the zero field value, so the matching effect is not easily seen. Presumably there is not sufficient thermal energy at 20 K and below to allow vortices to hop from one damage channel to the next under the Lorentz force from the circulating shielding currents. In the 2 – 5 T range, the hysteresis loops for the unirradiated and irradiated cases approach one another but the irradiated data are always higher.

To study the additive nature of the two types of pinning in more detail, the data at 35 K for the sample irradiated to a matching field of 1 T are parametrized in terms of the critical current density, J_c, and plotted in Fig. 3. Here the bump in the data for the irradiated sample (open triangles) is more apparent and clearly approaches the J_c values of the unirradiated sample (open circles). If the temperature is increased to 45 K, as shown in Fig. 4, J_c for the irradiated sample shows a peak at about 0.5 T and then it matches the unirra-

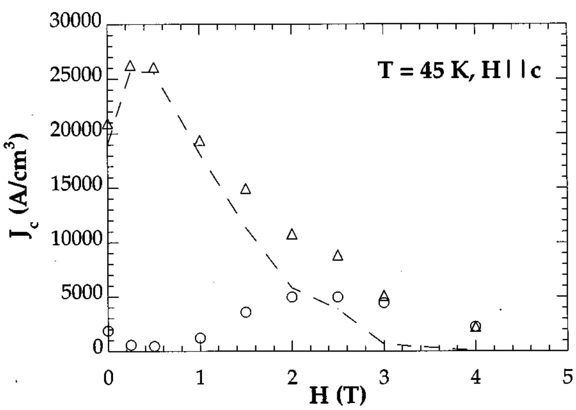

FIG. 4. Critical current density J_c, in the ab plane, at 40 K for the as-grown crystal (the open circle), the irradiated crystal with a 1 T ion dose along the c axis (the open triangle), and the difference between them (dashed line).

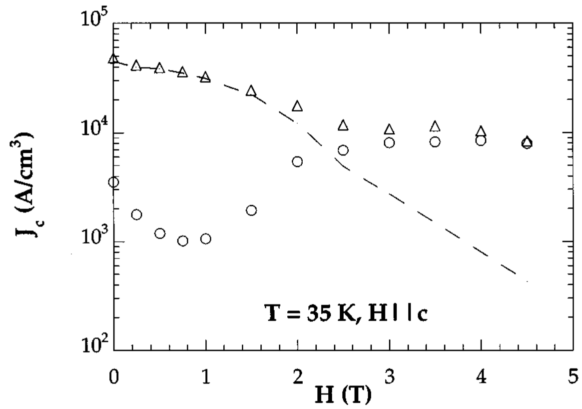

FIG. 5. Semilogarithmic plot of Fig. 3 to show a strong enhancement of J_c in the low field region.

diated sample above 3 T. The regions of small J_c are more readily seen on the semilogarithm plot of Fig. 5. Probably the most convincing data illustrating the additive character of the fishtail pinning and the irradiation channel pinning are in Fig. 3 where the unirradiated sample fishtail bump (open circles) is replicated in the data after irradiation (open triangles).

To study whether the rise in magnetization between 0 and 0.8 T in Fig. 1 really fits the matching model well, similar data were taken over an extended temperature range for both samples. The data reveal that there is only a limited temperature window where the matching effect is observed. Below 35 K, the long range rigidity of the flux-line lattice inhibits the single vortex motion, and the matching effect is difficult to observe. Above 55 K, the magnetic field dependence of the collapsing order parameter controls J_c, and the matching effect cannot be observed. Between 35 and 55 K, the position of the peak is only very weakly dependent on temperature as predicted from the simple model. For the 2 T sample, the peak occurs consistently at about 0.6 T, a value of about 1/3 the field expected if the damage tracks were regularly arranged instead of random. For the 1 T sample, the peaks occur consistently at about 0.4 T. The ratio of the peak field for the two samples is consistently about 1.5. A model that properly accounts for the rigidity of the flux-line lattice and the statistical spacing of the channels might give these values of the peak well below the value of equal areal density of defects and vortices.

IV. CONCLUSIONS

At temperatures below 35 K, flux pinning due to irradiation channels falls monotonically with increasing magnetic field and the effects of a matching between the vortex density and damage channel density are not seen. At higher temperatures of about 35 K where there is sufficient thermal energy to allow single vortex behavior, the matching effect is observed. For both of the samples reported here, the peak in J_c occurs at about half the magnetic field where the density of damage channels and density of vortices are equal. In the magnetic field region from 2 to 5 T, the fishtail effect is clearly present in the unirradiated sample, and it is preserved even after irradiated, as illustrated by the 35 and 45 K data of Figs. 3 and 4. In at least a rough way, the two pinning effects do seem to be additive. In the range of 4–5 T, far above the matching field, the fishtail pinning is comparable to the irradiation channel pinning.

ACKNOWLEDGMENTS

Work at Ames Laboratory was supported by the U.S. Department of Energy (DOE), Office of Basic Energy Sciences under Contract No. W-7405-ENG-82 (M.X., J.E.O., D.K.F., and M.J.K.). Work at the Argonne National Laboratory was supported by the U. S. Department of Energy (DOE), Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38 (J.A.F., J.D.H., U.W., and G.W.C.) and the work at Northern Illinois University and University of Chicago was supported by the NSF through the Science and Technology Center for Superconductivity under Contract No. DMR 91-20000 (B.D. and K.Z.).

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