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Effect of sample shape on the low-field peak in the magnetization of $YBa_2Cu_3O_{7-\delta}$

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We have measured the magnetic hysteresis in melt-textured $YBa_2Cu_3O_{7-\delta}$ of different specimen shapes: a platelet and a slab, both in the $\mathbf{H}\|c$ orientation. Significant differences in the magnetization especially at low field have been found. The low-field peak in the magnetization on the reverse leg appears to occur at a significantly higher field in the slab than in the platelet. This is tentatively explained by the effect of the geometry on the local magnetic field, which is turned from $\mathbf{H}\|c$ (as applied) in the slab towards $\mathbf{H}\perp c$ in the platelet.

The magnetic response of superconductors in the mixed state is governed by the critical state.[1] For the infinite slab or cylindrical geometry the value of the magnetization hysteresis is given as $\Delta M = J_c t/C$. Here t is the thickness of the slab (or diameter of the cylinder), J_c is the critical current density, and C is a geometrical constant, being 3 for the cylinder and 2 for the slab.

In an actual experiment the infinite geometries are rarely present. Typically plate- or disk-shaped specimens are used which have circular symmetry, but are thin along the direction of the applied field. This geometry has been of considerable interest recently[2-7] due to the strong demagnetizing and field-bending effects present. In particular the full penetration field for a slab is given by the product of J_c and slab half width, whereas for a thin disk it is approximated by the product of J_c and disk thickness.[3]

In this work we have carried out a direct comparison between two specimens cut from the same rod of melt-grown $YBa_2Cu_3O_{7-\delta}$, one in the shape of a plate, and the other in the form of a slab. In this paper we will focus on the low-field peak in the magnetization. A detailed analysis of the flux-penetration profiles will be published later.

Quasisingle crystalline specimens of $YBa_2Cu_3O_{7-\delta}$ were prepared with a zone-melting technique. For this first a rod consisting of cold isostatically pressed and then sintered $YBa_2Cu_3O_{7-\delta}$ was prepared. Then this rod was partially and locally melted in an optical image furnace. A typical growth velocity is 1 mm/h. The result is a rod which contains one or two grains only in the cross section. Specimens were then cut from this rod with a diamond saw, and oxygenated by slow-cooling them over several days to room temperature in an oxygen atmosphere.

The specimens measured here were a platelet with dimensions of $2.3\times 2.4\times 0.73(H)$ mm^3. The c axis is oriented along the thin axis (H) of the platelet. Specimen 2 is a slab with a dimension of $1.37(H)\times 3.82\times 0.86$ mm^3. Here the c axis is oriented along the axis marked H. The specimen contains a defect which runs approximately parallel to the current flow, thus not important for the present analysis. Both specimens were cut from a larger block, and were physically right next to each other during growth. For the measurement the magnetic field was oriented in both cases along the axis H, thus $\mathbf{H}\|c$. The critical temperature T_c was measured using an ac inductive technique. The T_c onset is 91.7 K, with a transition width (10–90 %) of about 1 K.

The magnetic moment was measured with a vibrating sample magnetometer. For the measurement the superconducting magnet was swept at a constant rate while the magnetic moment was continuously measured, while keeping the specimen at constant temperature. The magnetic field was determined by measuring the current in the superconducting solenoid. The sample space is cooled with helium gas, and any desired temperature between 2 and 120 K can be obtained with a heater.

In Fig. 1 part of the hysteresis loops around 0 T at 5 K for both specimens are shown. The slope of the initial penetration curve at 0 T is 1.36 for the slab, and 1.92 for the plate-shaped crystal. Analysis of the initial flux change in the reverse legs[8] gives a length scale of current flow corresponding to the sample size for the platelet. This method cannot be applied to slabs. In Fig. 2 the current density as a function of magnetic field is shown. It was calculated from the width of the hysteresis loop, and the geometry of the specimens using the standard expressions. The current density is almost identical for the two specimens in high field, while deviations occur in low field. The full penetration field can be estimated from the values of J_c calculated as well as from the minor loops taken. It is around 1 T for the slab, and about 2 T for the platelet.

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From a fabrication point of view (the two specimens were cut from the same place) the critical current density in the two specimens should be identical. Indeed this is what is found at high magnetic field. The slight difference found can be explained by the errors in measuring the sample dimensions. In low field, however, the deviations become too great, the J_c value being larger in the platelet. This must be a result of the different specimen shapes, since there are no other differences.

Particularly noteworthy is the position of the peak in the magnetization loop when the field is on its way to decrease to negative values. For the slab the maximum occurs at about -0.4 T, whereas for the platelet the peak is located at about -0.1 T, being almost symmetric about 0 T. This is the case despite the fact that the minor loops show that the magnetic field trapped in the specimens is of order 1 T for the slab, and 2 T for the platelet.

The physical origin of this peak in a slab can be understood qualitatively. The equilibrium magnetization is neglected in this consideration, and the critical current is assumed to arise from bulk pinning, which are good assumptions for $YBa_2Cu_3O_{7-\delta}$ at 5 K. J_c is assumed to have a maximum at $H=0$. When the applied field is decreased from large positive values the internal field in the specimen center is larger than the applied field by the value of the trapped field h^*. Thus the applied field has to become negative to lower the internal field inside of the specimen. This leads to a peak in the magnetization between zero and the full penetration field h^* (which, in fact, is somewhat ill defined at this point due to the field dependence of J_c) when the field distribution is such that maximum currents can flow. If there was no field dependence to J_c then no such peak would occur. If the self-field of the specimen was very small (by reducing the slab width, for example) the peak is expected to shift to smaller field. For the platelet the self-field is larger, and thus the peak is expected at a larger negative field than for the slab, in contradiction to the experimental result.

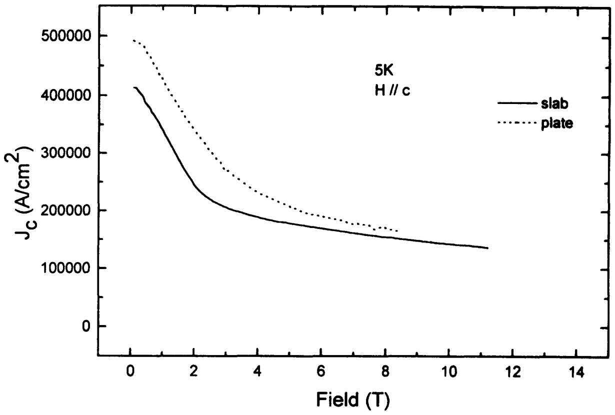

FIG. 2. Critical current density vs magnetic field at 5 K for slab- and plate-shaped specimens.

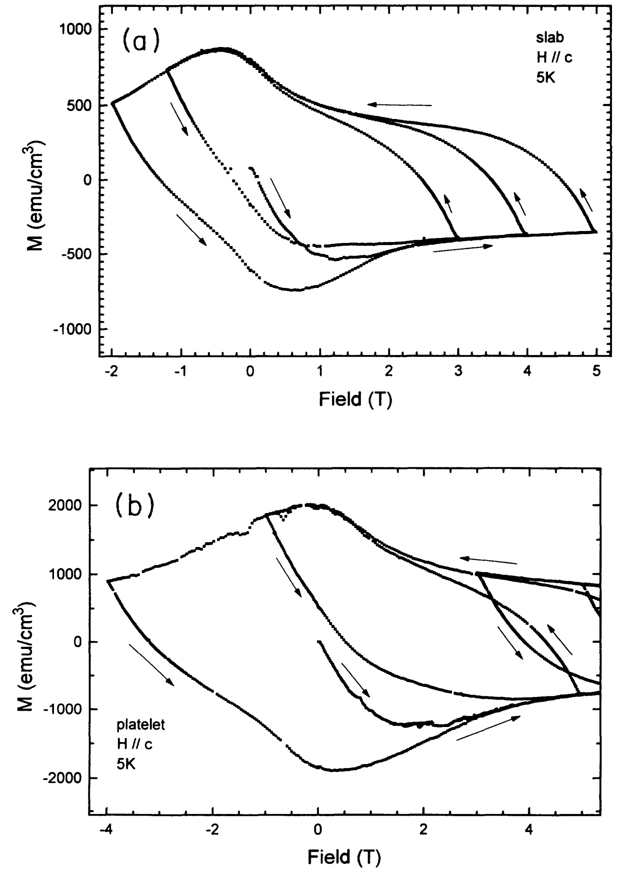

FIG. 1. Magnetization at 5 K of (a) slab-shaped and (b) plate-shaped specimen. The data were taken with a field ramp of 8.3 mT/s.

As shown previously[3,4] the magnetic-field distribution for a platelet is complicated. The radial component of the field generated by the plate will change the local-field direction, especially on the plate surfaces. Here there will be a significant field component along the a,b plane direction. However, the field dependence of J_c will be dependent on whether the field is parallel to the c or the a,b direction. In general J_c is lower and depends more strongly on field when $\mathbf{H} \| c$.[9]

Thus we can qualitatively interpret the behavior found for the platelet When the field is lowered the local field rotates away from the c axis towards the a,b plane. Thus the value of J_c is enhanced, and the field dependence of J_c is reduced, moving the peak in the magnetization towards zero, as is experimentally observed. It should be noted that calculations[10] using a modified critical-state model seem to reproduce our measured effect without introducing any anisotropy in the field dependence of J_c. It remains to be seen if measurements of the type presented here on isotropic specimens can confirm this. In order to quantitatively verify this picture model calculations using an anisotropic J_c vs field dependence appear useful as well.

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