Investigation of pinning and dissipative processes in the $YBa_2Cu_3O_{7-x}$ superconducting system

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A contactless mechanical method was applied to ceramic samples of $YBa_2Cu_3O_{7-x}$ high-temperature superconductors in a study of the pinning of the Abrikosov vortices and of the dissipative processes associated with destruction of the vortex structure. The dependence of the pinning force on the magnetic field was determined.

Most of experimental investigations of high-temperature superconductors have been carried out so far on polycrystalline samples. It has been found that in the case of single-crystal films of high-temperature superconductors the critical current densities j_c can exceed 10^6 A/cm^2 in zero magnetic field even at liquid nitrogen temperatures,[1] whereas in the case of bulk polycrystalline samples the value of j_c is only 10^3 A/cm^2 under the same conditions.[2] Such values of the critical current density have been obtained for high-density samples which unavoidably acquire a texture during preparation, which distorts the real pattern of the pinning of Abrikosov vortices. On the other hand, in low-density ceramic samples the pinning influence of macroscopic defects, created in the process of establishing the microstructure by compaction, is considerably less. Therefore, we carried out direct measurements of the pinning force specifically on ceramic samples and the low values of the critical current density were not regarded as a disadvantage, at least from the point of view of accurate measurement of the pinning force.

We investigated the pinning and dissipative processes in high-temperature $YBa_2Cu_3O_{7-x}$ superconductors by a torsion method.[3] In this method the pinning force was deduced from the measured mechanical moment exerted by vortices on a superconducting cylinder. Since the vortices are pinned at inhomogeneities of the crystal lattice, a magnetic field acting on the vortices tending to align them along the field to orient a sample with vortices along a specific direction until the vortices are detached from their pinning centers by an external agency. Determination of the critical mechanical moment or torque at which the vortices are detached from the pinning centers makes it possible to estimate the pinning force per vortex.

In addition to this static method for the determination of the pinning force, one of the authors of the present paper developed a dynamic method[5] which is more suitable for determination of weak pinning forces. This method is based on a study of the dissipative processes that occur in the mixed state in superconductors. We shall describe it briefly. If a superconducting cylinder is suspended by a thin elastic filament and subjected to a magnetic field perpendicular to it, then in a field exceeding the first critical value ($H > H_{c1}$) the cylinder is penetrated by the Abrikosov vortices.[6] Rotation of the cylinder about its axis (by an angle φ) relative to the direction of the external magnetic field H imposes a mechanical moment on the pinned vortices, which tends to rotate the sample back to its initial position. An increase in φ increases the torque acting on the vortices and for $\varphi > \varphi_c$ the vortices begin to separate from the pinning centers under the influence of the external magnetic field and they start to move in the opposite direction (the vortices return to the orientation along H).

If such a system with vortices is set in vibrational motion and the vibration frequency ω as well as the logarithmic damping decrement δ is determined, then at low amplitudes of the vibrations, when the vortices are still pinned to lattice defects, these vortices increase the vibration frequency (effective elasticity) of the suspended system and the damping δ is then minimal. On increase in φ and, consequently, of the force acting on the vortices, we reach a situation ($\varphi = \varphi_c$) when the vortices begin to separate from the pinning centers, which naturally increases δ and reduces ω. It therefore follows that measurement of the critical amplitude gives the critical torque and, consequently, the average pinning force. The logarithmic damping decrement of the vibrations is known to be a measure of the dissipated energy. Consequently, a study of such torsional vibrations of a superconductor suspended by a thin elastic filament can be used to determine both the pinning force of the Abrikosov vortices and the dissipative process associated with the motion of these vortices.

We carried out experiments of this type in order to investigate the pinning and dissipative processes in $YBa_2Cu_3O_{7-x}$ high-temperature superconductors.

A sample of $YBa_2Cu_3O_{7-x}$ was made in the form of a disk 6 mm in diameter and 3.5 mm thick; it was placed in a special crystal holder and the moment of inertia of the holder was increased by an additional disk with a moment of inertia 84.85 g·cm^2. The whole system was placed between the poles of an electromagnet which generated a magnetic field perpendicular to the axis of the sample. The apparatus was connected to an SM-3 computer which measured the frequency and the logarithmic damping decrement of the vibrations, controlled the experiments, and analyzed the experimental results. The apparatus used was described in detail by us in Ref. 7.

We first studied the influence of a magnetic field on the vibration period and on the logarithmic damping of a suspended system with a sample of $YBa_2Cu_3O_{7-x}$ at liquid nitrogen temperature. In zero magnetic field we found that the period and the decrement were $\tau = 10.95$ s and $\delta = 1.60 \times 10^{-2}$, whereas in a field of $H = 80$ Oe they were $\tau = 10.78$ s and $\delta = 2.01 \times 10^{-2}$.

The effects appeared more clearly at liquid helium temperatures. Therefore, we shall report here the data obtained

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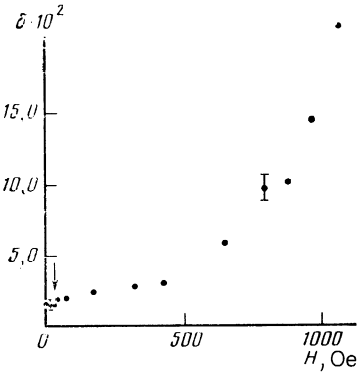

FIG. 1. Dependence of the logarithmic damping decrement δ of vibrations on an external magnetic field H applied at $T = 4.2$ K to $YBa_2Cu_3O_{7-x}$.

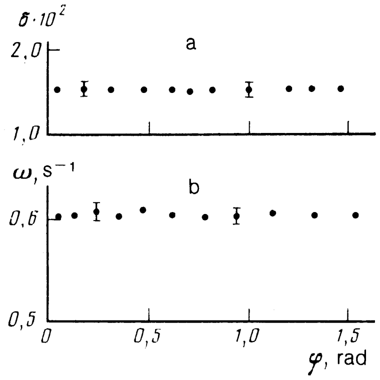

FIG. 2. Dependence of the damping δ (a) and of the vibration frequency ω (b) on the vibration amplitude at $T = 4.2$ K in a field $H = 10$ Oe.

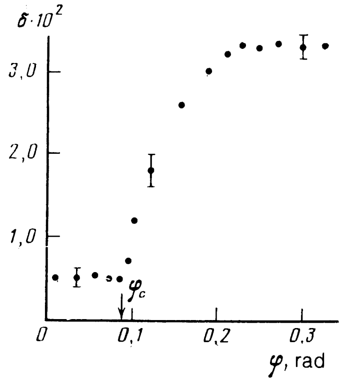

FIG. 3. Dependence of δ on the vibration amplitude $\varphi (H = 1200$ Oe).

at liquid helium temperature of $T = 4.2$ K. As expected, in weak external magnetic fields the damping was independent of the field intensity (Fig. 1). Hence, the field did not penetrate the superconductor. A further increase of H (above the value identified by an arrow) caused the damping to increase with the field. This indicated that the field began to penetrate the superconductor. Earlier experiments[3-5,7] on type II superconductors showed that the change in the damping began when the Abrikosov vortices penetrated the bulk of the superconductor. Consequently, the field identified by the arrow in Fig. 1 was the first critical field H_{c1}.

These experiments indicated[3-5] that in magnetic fields $H < H_{c1}$ both the damping and the vibration frequency of the suspended system were independent of the vibration amplitude in the case of type II superconductors. Our experiments indicated that in the case of the $YBa_2Cu_3O_{7-x}$ system subjected to fields $H < H_{c1}$ the damping δ and the vibration frequency ω were again independent of the amplitude (Fig. 2). When the magnetic field penetrates the sample in the form of flux quanta and the resultant vortices are pinned by lattice imperfections, the sample in the mixed state should exhibit an amplitude dependence of the damping and frequency. In fact, we found that about H_{c1} both the damping and the vibration frequency varied with the amplitude (Figs. 3 and 4). It is clear from Fig. 3 that in the range $\varphi > \varphi_c$ the damping began to vary with the amplitude δ and increased strongly as a function of the latter. This was due to detachment of the vortices from the pinning centers and their subsequent motion in the investigated crystal, which was accompanied by additional dissipation of the energy. This confirmed the amplitude dependence of the vibration frequency (Fig. 4). Clearly, at low amplitudes the frequency ω was independent of φ and the amplitude dependence began to appear at the same value of $\varphi = \varphi_c$. Taking this value as the critical amplitude, we found the average force per vortex from Ref. 8:

$$F_{pv} = \frac{3f\varphi_c}{2NR^2},$$

where f is the elastic moment of the suspension; N is the number of vortices in a sample calculated from the magnetic field intensity and from a flux quantum, and R is the radius of the sample.

The dependence of the pinning force on H plotted in this way is shown in Fig. 5. These results and the familiar expression were used to find the critical current density

$$j_c = \frac{10F_{pv}}{\Phi_0},$$

where Φ_0 is a flux quantum defined by $\Phi_0 = hc/(2e)$. In the case of the investigated ceramic samples an estimate of j_c

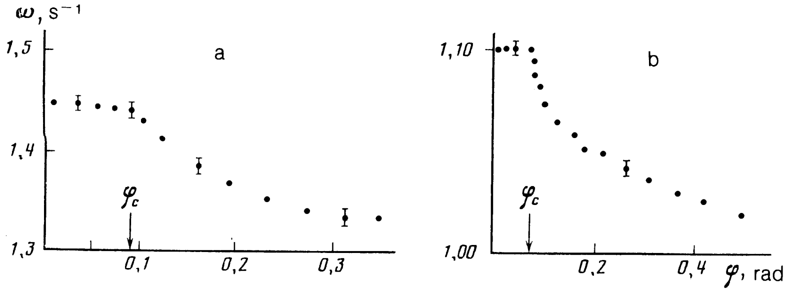

FIG. 4. Dependence of the vibration frequency $\omega = 2\pi/T$ on φ for different magnetic fields $H = 1200$ Oe (a) and $H = 800$ Oe (b).

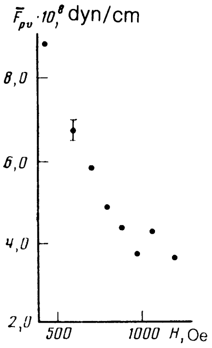

FIG. 5. Dependence of the average pinning force $\overline{F}_{pv}$ on H at $T = 4.2$ K for $YBa_2Cu_3O_{7-x}$.

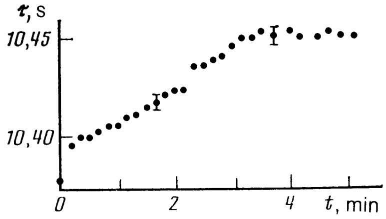

FIG. 6. Dependence of the vibration period τ on the time t from the moment of application of a magnetic field $H_0 = 1200$ Oe at $T = 4.2$ K to $YBa_2Cu_3O_{7-x}$.

obtained using the above expression gave 2–4 A/cm^2, which was between four and six orders of magnitude less than for type II superconductors, indicating a poor contact between superconducting grains.

When the field $H = 1200$ Oe was switched off, we determined the time dependence of the vibration period of the suspended system. We plotted the results in Fig. 6. Clearly, the vibration period gradually increased. This was evidence of a gradual disappearance of vortices (they escaped from the bulk of the sample); in other words, it indicated decay of the vortex structure which took an anomalously long time of about 3.5 min. This decay indicated the presence of an anomalously strong creep of the flux in the investigated samples. Similar effects had been reported also for the ceramic $La_{1.85}Sr_{0.15}CuO_4$.[9]

This mechanical method was used in Ref. 10 to investigate the pinning in $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_{7-x}$ ceramic samples. As in the present study, very weak pinning was observed, and a field of 10–120 Oe was sufficient to ensure that the flux penetrated "weak links" binding the grains, whereas in fields in excess of 120 Oe the flux began to penetrate the superconducting grains themselves. The dependence of the vibration period on the relaxation time obtained in Ref. 10 was similar to our dependence in Fig. 6. An analysis of the possible reasons for the very weak pinning should allow also for the possibility of pinning many flux vortices captured between grains. Then a calculation of the pinning force could not be carried out by the usual formula[8] for an Abrikosov vortex.

We conclude by noting that our results demonstrated the potentialities of the contactless mechanical method in investigations of the pinning in high-temperature superconductors. Unfortunately, the measurements were carried out only on ceramic samples. The pinning force in these samples did not represent fully the situation in single crystals, for which the critical current density estimated from the Bean expression and the magnetization measurements amounted to at least 10^4 A/cm^2 at 77 K. The currently available single-crystal flakes of $2\times2\times0.05$ mm dimensions have a very small volume, so that it would not yet be possible to carry out reliable measurements on these flakes by the contactless mechanical method.

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