Effect of surface and volume defects on the dissipative processes in type-II superconductors

Dzh. G. Chigvinadze

Physics Institute, Georgian Academy of Sciences
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A mechanical procedure is proposed for investigating dissipative processes in the mixed state; this procedure is more sensitive by several orders of magnitude than the known electric procedure. The effect of surface and volume defects on the dissipative processes caused by the motion of Abrikosov vortices is studied.

The present paper is devoted to the question of the role of surface and volume defects in dissipative processes of type-II superconductors. The mechanical method proposed by us for the study of the dissipative processes[1], unlike the electric methods, makes it possible to investigate these processes in pure form without participation of a large transport current, which is inevitable in current-based experiments[2].

The large critical current J_c causes all the Abrikosov vortices to break away from their pinning centers and to undergo collective motion accompanied by energy dissipation. The resistance to flow ρ_f (ρ-flow) is investigated under such conditions. To be sure, in the initial part of the V(J) curve there is a region of vortex creep, but this region is difficult to investigate by current-based methods. A mechanical procedure makes it possible to "penetrate" into the creep region by investigating dissipative processes at various amplitudes of axial-torsional oscillations of the superconductor in a transverse magnetic field. With changing amplitude, we change the number of the pinned vortices.

Thus we can, in principle, cover the entire range from the breakaway of the vortices from the pinning centers as a result of thermal activation (creep), to complete detachment of all the vortices (flow). To this end, we need apparatus that ensures the possibility of investigating dissipative processes of type-II superconductors in a sufficiently wide oscillation-amplitude region.

In our earlier studies of dissipative processes, we used an installation in which the vibrational system was secured in a vertical direction with the aid of a molybdenum filament placed in the lower part of the Dewar flask, limiting the oscillation amplitude to $\sim 1 \times 10^{-1}$ rad[1]. For the present study, we constructed an installation that made it possible to investigate the dissipative properties of superconductors in a wide amplitude interval, up to 5–10 rad. It constitutes a straight pendulum (see Fig. 1).

It should be noted that the proposed mechanical procedure is much more sensitive than the electrical procedure. Indeed, the minimal dissipation measured in the latter case is equal to $P = j_c SV$, where j_c is the critical density of the current, S is the cross section of the sample, and the V is the minimal measured potential difference. For example, for samples similar to those used in the present paper we would have $j_c \approx 10^2$ A/cm^2, $S \approx 10^{-3}$ cm^2, and $V \approx 10^{-8}$ V, whence $P \approx 10^{-2}$ erg/sec. Yet in our case $P = f\delta\varphi^2/T$, where f is the torque of the suspension, δ is the damping decrement, T is the period, φ is the minimal measured amplitude,

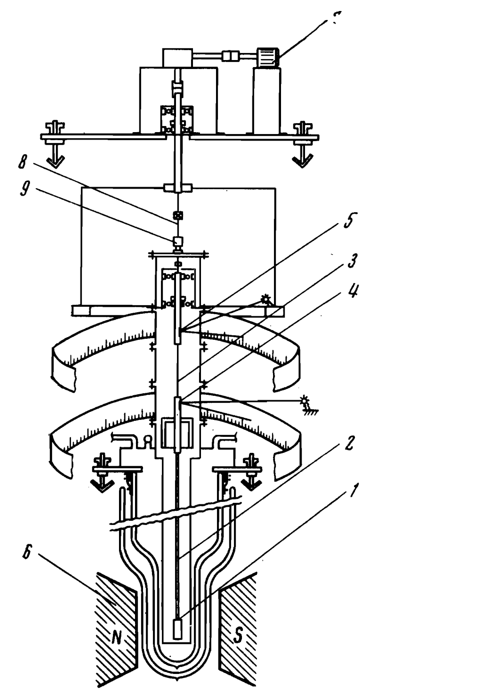

FIG. 1. Diagram of installation: 1—sample; 2—glass rod; 3—elastic filament of lead brass (filament length L = 100 mm, filament diameter 40 μ), 4, 5—mirrors; 6—electromagnet; 7—electric motor; 8—shaft; 9—seal.

with f = 2.372 dyne-cm, $\delta \approx 10^{-3}$, $\varphi \approx 10^{-3}$, and $T \approx 15$ sec, hence $P \approx 10^{-10}$ erg/sec.

Sample 1 was prepared in the form of a cylinder made of a type-II superconductor. It was fastened to a glass rod 2 with a moment of inertia I = 13.63 g/cm^2, freely suspended to an elastic filament 3 (filament length L = 100 mm, diameter d = 40 μ), placed inside the helium Dewar under its cover. On both sides of the filament there were placed two mirrors 4 and 5, one of which (5) was mounted on a shaft 8 passing through a seal 9. This shaft could be rotated with the aid of an electric motor 7. The rotating part of the apparatus was used to measure the pinning force[3,4]. The other mirror (4) was secured to the glass rod to which the sample was fastened. The oscillations were registered both visually and with the aid of a light beam reflected from mirror 4, as well as with the aid of electronic circuitry described in[5]. In the investigation of the dissipative processes, the shaft 8 was fixed in a definite position.

As indicated in[1], the logarithmic damping decrement δ of the oscillations in the mixed state depends on

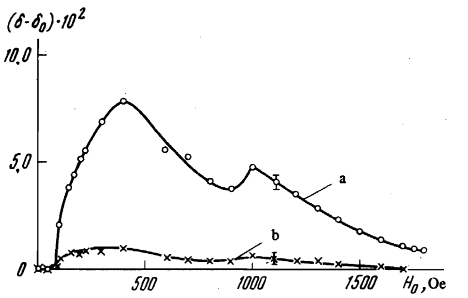

FIG. 2. Dependence of the logarithmic damping decrement of the oscillations on the intensity of the external magnetic field. Sample $Ta_{70}Nb_{30}$, electrically polished: a—φ = 0.2 rad, b—φ = 2-5 rad; δ_0 is the logarithmic damping decrement of the system without the sample.

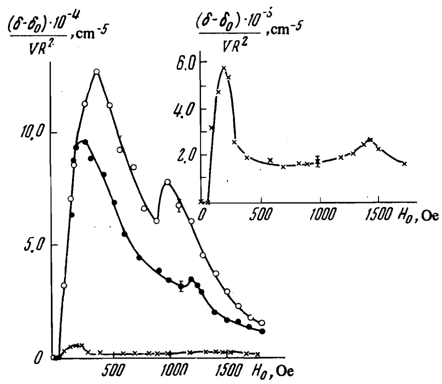

FIG. 3. Dependence of logarithmic damping decrement on the intensity of the external magnetic field; ○—in an ideal crystal; ●—in crystals with surface defects and X—in crystals with volume defects (with $\Delta l/l$ = 42%) (φ = 0.2 rad, δ_0 is the logarithmic damping decrement of oscillations without a sample).

the intensity of the external magnetic field H_0. Figure 2 shows the $\delta(H_0)$ dependence for a thermodynamically reversible single crystal (the surface of such a crystal is mirror-finished and was worked by electric polishing).

It is clear that the defects on the crystal surface and in the volume of the crystal lattice should act on the dissipative processes in different ways: the surface defects will restrain (pin) only the end parts of the vortices, whereas volume defects will pin the vortices over the entire length of the vortex filament. To explain the influence of the surface and volume defects on the dissipative processes in type-II superconductors ($Ta_{70}Nb_{30}$ single crystals), we represent on a single plot the results of an investigation of the dissipative processes in "defect-free" crystals, crystals with surface defects, and crystals with volume defects (produced by a compressive deformation $\Delta l/l$ = 42%). We note that the samples differed in their dimensions, especially in their diameters.

To compare the results obtained in experiments with different samples, the logarithmic damping decrement (the energy dissipation in one half-period) should be reduced to a unit volume of the sample (i.e., should be divided by $R^2 l$[1), where R is the radius of the sample and l is its length), and also divided by R^2, since the number of vortices piercing the sample and the moment of the given force are proportional to R. The curves obtained in this manner are shown in Fig. 3. (φ = 0.2 rad). Comparison of these curves shows that both the surface and the volume defects decrease the damping of the oscillations. With increasing number of defects, the energy dissipation decreases. This result agrees with the assumption that the energy dissipation is due to motion of Abrikosov vortices and is large at relatively large concentration of the free vortices.

However, certain details of the experimental curves are less understandable. For example, it is not clear why the curves for polished and spark-finished crystals coincide in the interval $H_{c1} < H_0 < 250$ Oe. This agreement means that at $H_0 \gtrsim H_{c1}$ the surface defects do not influence the attenuation, although their presence could not help but change the concentration of the free vortices.

The very abrupt decrease of the damping in strongly deformed crystals is also in contradiction to the concept of energy dissipation by free vortices only, since an investigation of very strongly deformed samples ($\Delta l/l$ = 42%) has revealed a sharp decrease of the average pinning force[4,6]. This sharp decrease of $\overline{F}_p$ is explained in the following manner. A 42% deformation of the sample produces such a large number of dislocations that the distance between them, $l = 3.0 \times 10^{-6}$ cm, is smaller than the radius of the core of the vortex, $\xi = 4.5 \times 10^{-6}$ cm. Consequently, in such a crystal there are no inhomogeneities of the crystal lattice, whose dimensions $l \approx \xi$ and on which the vortex line could be effectively pinned (the crystal is homogeneous, as it were, to the vortex), and this explains the abrupt decrease of the pinning force.

One cannot exclude the possibility that these disparities can be attributed at least in part to the appreciable influence exerted on the damping of the oscillations of the pinned vortices. The agreement between the initial sections of the $\delta(H_0)$ curves of polished and spark-finished crystals can in this case be attributed to the fact that the motion of the free vortex and the motion of vortices that are pinned mainly on the surface of the sample lead at $H_0 \approx H_{c1}$ to approximately the same energy dissipation, which is proportional in this case to the total number of vortices.

As to the decrease of the damping of the oscillations of a strongly deformed crystal, one cannot exclude the possibility that the presence of a large number of defects, even at a very small pinning force, greatly limits the freedom of displacement of the overwhelming majority of vortices—the vortices seem to move "in spurts" over small distances.

The first of the maxima in our plot, which is more clearly pronounced, is observed in all single-crystal samples at any oscillation amplitude. It shifts towards H_{c1} when both surface and volume defects are introduced. The second maximum, which is less strongly pronounced and is frequently not observed at all, shifts towards H_{c2} under the same conditions.

The question of the shifts of these maxima as a result of introducing defects into the crystal lattice still remains open at present.

In conclusion, the author thanks É. L. Andronikashvili for stimulating interest in the work and V. P. Galaĭko, Yu. G. Mamaladze, and Dzh. S. Tsakadze for its discussion and for valuable remarks.

[1)]It should be noted, however, that if the vortex pinning were a pure surface effect, then it would be necessary to divide by Rl instead of by $R^2 l$, i.e., a more correct relative value would be the ratio $\delta/R^3 l$.

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