Pinning and plastic deformation of vortex lattice in type-II superconductors

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(Submitted June 27, 1974)
ZhETF Pis. Red. **20**, 185–188 (August 5, 1974)

We consider the possibility of overcoming the obstacles to the motion of a vortex lattice due to its plastic deformation.

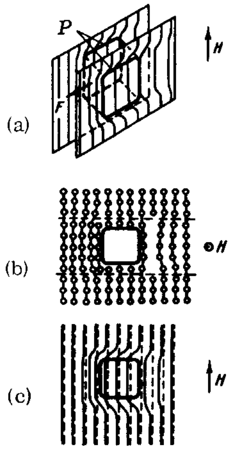
The rigidity of type-II superconductors, as is known, is due to the interaction of the vortices with the inhomogeneities of the crystal (defects, inclusions of foreign phases, etc). The pinning of the vortices by the inhomogeneities of the crystal structure leads to a fastening of the vortex lattice (VL), and the lattice cannot be moved by electrodynamic forces unless these forces exceed a certain critical value. In this connection, the problem of determining the critical conditions, and in particular the critical current (I_c), reduces usually to a determination of the local forces of interaction between the VL and each inhomogeneity, and to a statistical averaging of the local pinning forces. In many real cases, however, not all the vortices are pinned by inhomogeneities, and the condition that the local pinnings be conserved is a necessary but sufficient condition for the prevention of the displacement of the entire VL: the nonpinned vortices can "flow around" the VL sections that are restrained by the pinning centers. This gives rise to a relative mutual displacement of individual sections of the VL, i.e., to plastic deformation of the vortex lattice. The possibility of "flow around" the pinned or less mobile regions of the VL by the more mobile ones, which exists in any system with spatially-inhomogeneous pinning, is not taken into account as a rule when a pinning theory is developed or when the experimental results are interpreted (see, e.g., the reviews).[1,2]1) The purpose of the present article is to call attention to the important role played in processes that determine the rigidity of type-II superconductors, by the inhomogeneous plastic deformation of the VL, which consists of the creation (annihilation) and displacement of the vortex-lattice defects.

Let us consider a concrete example, viz., a superconductor containing macroscopic inclusions of the normal phase (the inclusion radius is $R \gg a$, where a is the period of the VL). All the inclusions are identical and are equally spaced a distance L apart, with $L > R$. As is well known, the pinning in such a system is due to the adhesion of the vortices to the surfaces of the inclusions. Assuming that this adhesion is magnetic in nature, the critical force necessary to overcome the pinning force is equal to[5]

$$p = BI_c = (k/\kappa^3)\, B_{c2}^2 b^{1/2}(1-b)(R^2/L^3), \quad b \equiv B/B_{c2}, \tag{1}$$

where B is the induction, κ is the Ginzburg-Landau parameter, B_{c2} is the induction corresponding to the second critical field, and k is a numerical coefficient on the order of unity. This formula describes well qualitatively the experimental results obtained in the study of Pb-Bi eutectics[5] and of certain other composite materials.

Let us assume, however, that the pinning is not disturbed: the interaction of the vortices with the interphase surface is strong enough, and there is no displacement of the VL on the particle surfaces. Then, when an external force is applied (say in the presence of a current I) the displacement of the VL as a whole leads to elastic deformation of the VL in the vicinity of the particle. The problem of the relative motion of the VL and of the particles reduces to a clarification of the conditions under which the particle "punctures" through the "vortex crystal" under the influence of the force $F = BIL^3$. The elementary act of the "puncturing" is the



a) Dislocation loops in slip planes (P), b) section through VL and the slip planes, c) vortex structure in the slip plane.

displacement of the particle over the period a. When the particle moves in the close-packing direction of the VL, the irreversible displacement of the particle relative to the lattice is equivalent to the formation of two dislocation loops in the slip planes that bound the particle (see the figure).[2)] The energy criterion for the occurrence of the process is equality of the work of the external force F to the energy of the dislocation loops:

$$Fa = 2(\mu a^2/2\pi)[\ln(8R/a) - 1]2\pi R \approx k'\mu a^2 R, \quad (k' \sim 1), \qquad (2)$$

where $\mu = (c_{44}c_{66}/\tau)^{1/2}$ is the average shear modulus of the VL,[2] and $k'\mu a^2/4$ is the linear energy of a dislocation loop[6] of radius R. It follows therefore that the volume density of the external forces, which leads to the plastic puncturing of the particle through the VL, is equal to

$$p_{pl} = BI = F/L^3 = (k''/\kappa)\,\phi_0^{1/2}\,B_{c2}^{3/2}\,b^{1/2}(1-b)(R/L^3), \qquad (3)$$

where k'' is a numerical coefficient on the order of unity. Comparison of (1) and (3) shows that the plastic flow becomes limiting, i.e., $p_{pl} < p$ at $R > R_b \sim \kappa^2 \xi$, where ξ is the coherence length. Indeed, the available experimental data[2,5] show that when the particle radius is varied the quantity $BI_c L^3/R^2$ ceases to be constant in the region of large particles and decreases like $1/R$.[3)]

Obviously the question of the relation between the "unpinning" process and plastic deformation is quite general in character. Electrodynamic forces displace the VL, and as a reaction local pinning forces are produced in its volume, and lead to an inhomogeneous elastic deformation. When the external force is increased, the inhomogeneous elastic deformation increases, and a critical state is reached, at which the vortex start to become detached from the pinning point, or else plastic deformation of the VL sets in under the influence of the local stresses. In real cases, the displacement of the VL begins in the weakest spot, from which the displacement zone propagates and gradually overcomes the obstacles on its boundary. To realize this inhomogeneous motion of the VL it is necessary that individual parts of the VL be able to move relative to one another, i.e., the resistance to the lattice displacement depends entirely on its plastic compliance. The development of plastic deformation in local regions depends in this case not only on the changing stress fields in these regions, but also on the initial defect structure.[4)]

1)By way of exception, mention should be made of[3], where the possibility of "flowing around" is attributed to local loss of stability by the VL relative to displacement, and the critical current for a simple one-dimensional model is determined on this basis.[4]

2)In an ordinary crystal, the puncturing can be accompanied by formation of a pair of prismatic loops, an interstitial one in front of the particle and a vacancy behind it.[6] No prismatic loops are produced in the VL because of the postulated condition that the vortex lines remain unbroken inside the superconductor. It is assumed also that no vortex creation or annihilation takes place inside the volume.

3)If the particles have anisotropic shapes, plastic flow should be accompanied by an appreciable variation of the function $BI(b)$ when the particle orientation relative to the field is changed. Inasmuch as $p_{pl} \sim [(c_{44}c_{66})^{1/2}R + c_{66}R']a$, where R and R' are the screw and edge components of the dislocation loop, we get $p_{pl} \sim c_{66}a \sim b^{-1/2}(1-b)^2$ for needle-shaped particles elongated along the field ($R' \gg R$), unlike the expression (3) for particles transverse to the field.

4)The condition under which the dislocation representations are valid is that the length characterizing the inhomogeneity of the pinning forces be large in comparison with the VL parameter a.

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