

SUPERCONDUCTORS

The mysteries of plastic motion

Understanding plastic motion of solids — in which atoms change their neighbours as they move — is complicated because it is discontinuous and does not conserve energy. An elegant study of vortex dynamics in superconductors provides new insights.

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Plastic motion of solids governs many processes in our physical world. On geological timescales, plastic motion is responsible for the topography of the landmasses of the Earth, for the drift of the continents, and for the regeneration of the Earth's crust from sources at the mid-ocean ridges. On shorter time scales, plastic motion produces cataclysmic events such as earthquakes and avalanches. Man-made structures are subject to plastic motion as well, the leaning tower of Pisa being a notable example. On page 477 of this issue, M.-Carmen Miguel and Stefano Zapperi analyse plastic motion in a particularly elegant and accessible geometry, the Corbino disk¹. Their molecular dynamics simulations reveal new insights into the plastic motion of vortices in superconductors and other self-assembled nanostructures subject to the action of shearing forces.

Despite its ubiquity and importance, plastic motion holds many secrets that we find difficult to unlock. One of the reasons is the lack of a comprehensive conceptual framework for plastic motion. Static structures in equilibrium are described by powerful energy minimization principles. Whether the object of interest is the Golden Gate Bridge or a quantum dot, we can analyse its stability and internal structure by minimizing the potential energy and interaction energy of its composite parts. No such unifying principle governs plastic motion. Once a material passes its elastic limit, atoms begin to move past each other and energy is no longer conserved. Tears appear in the atomic fabric where velocities change discontinuously within a single lattice constant. Without energy conservation and continuity to simplify the problem, plastic motion can be analysed only by following the trajectory of each atom obtained by solving the microscopic equations of motion.

The system chosen by Miguel and Zapperi to study plastic motion is at first sight surprising. They do not study the atomic matter that has been the domain of plastic motion since the time of Newton and Hooke. Rather, they focus on vortex matter, composed of interacting magnetic flux lines in superconductors. Magnetic fields enter most superconductors as tubes of flux, each tube consisting of a central magnetic field surrounded by a circulating supercurrent that separates it from the relatively field-free region outside the tube.

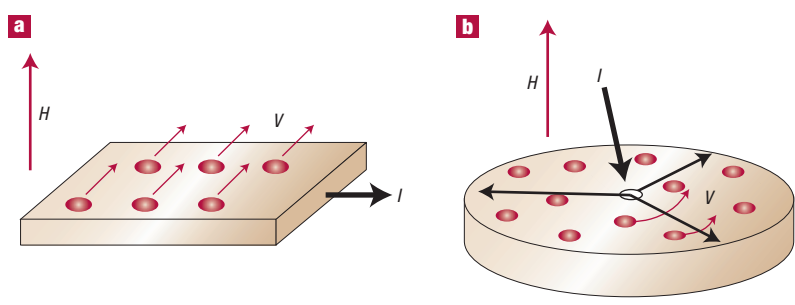


Figure 1 Investigating the dynamics of vortex matter. **a**, The conventional geometry for investigating vortex dynamics in superconductors under an applied current (I) and magnetic field (H). The current density and Lorentz force are uniform, and the vortices (represented by the red spots) are driven uniformly across the sample with velocity V . This geometry does not give rise to a shear force unless artificial 'pinning' defects are introduced. **b**, The Corbino geometry used in the simulations of Miguel and Zapperi¹ and in earlier experiments^{3,4}. The current density and Lorentz force vary inversely with radius, introducing shear forces that eventually induce a dynamic phase transition from elastic to plastic motion.

The circulating supercurrent gives rise to the name vortex for each tube of flux². Maxwell's equations require vortices to repel one another, leading to their regular arrangement on a hexagonal lattice. This perfect hexagonal lattice can be disordered by randomly placed material defects in the superconductor, such as grain boundaries or impurity clusters, that 'pin' or trap vortices at locations off the lattice sites to form glassy, amorphous states. There is a rich phase diagram of crossovers and phase transitions among the lattice, liquid, and glassy vortex states. The analogy between the structural configurations and phase behaviour of vortices and of atoms leads to the name vortex matter.

Miguel and Zapperi are concerned not with the structure of vortex matter but with its dynamics³. In the presence of a transport current in the superconductor, vortices feel a Lorentz driving force with a magnitude proportional to the current density and a direction that is transverse to both the current direction and the applied magnetic field. The conventional transport geometry shown in Fig. 1a injects a uniform current density along a slab of superconductor, and the vortices move in response to a uniform transverse Lorentz force. In contrast, the Corbino geometry^{3,4} (Fig. 1b) creates a natural gradient in the current density and the Lorentz force. Current injected at the centre of the disk spreads out as it moves radially to the perimeter, creating a current density that varies inversely with radius from the disk centre. The Lorentz force drives the vortices in circles around the centre of the disk. As the Lorentz force is proportional to the current density, it varies inversely with radius as well. Thus the Corbino geometry introduces a steady-state shear driving force on the vortex solid, a situation that is difficult to achieve in atomic solids.

The molecular dynamics simulations reported by Miguel and Zapperi show an unconventional kind of plastic motion. At low shear force (that is, low current

density) the vortex solid moves as an elastic body, the vortices keeping the same neighbours throughout the motion. The lattice rotates with the outer vortices moving faster than the inner ones. The Lorentz driving force, however, varies inversely with the radius, putting an elastic strain in the lattice as it rotates. As the shear force is increased, the strain eventually exceeds the elastic limit of the lattice, and a transition from elastic to plastic motion occurs. This dynamic phase transition attracts strong theoretical attention in the context of the Corbino geometry⁵. The question is, how will the rotating system relieve the strain?

Conventional wisdom might suggest that the rotating lattice will tear along a circle, introducing a line of slip separating sections of the lattice rotating at different angular velocities. In this classical response, the line of slip would be marked by a set of dislocations. However, the simulations find something very different. Dislocations are formed near the centre of the disk, but then fan out in several directions, eventually migrating to the perimeter. The plastic response is not localized on a set of slip lines but distributes itself throughout the entire system. At higher shear, another dynamic response is seen. Here the dislocations assemble into a set of dense 'grain boundaries' that extend radially across the disk. These lines of dislocations are neither rigid nor stationary — they rotate slowly around the centre of the disk and waver as the vortices move through them on their circular orbits.

The new form of plastic behaviour observed in these simulations leaves us with several messages. The science of dynamics is far from mature — we have

not yet discovered its higher principles, such as a variational principle that predicts and classifies the rich dynamic structures we have glimpsed. Rather, we must depend on experiments and particle simulations that reveal small insights about particular situations. We have, however, made progress. The Corbino geometry opens new possibilities for 'clean' experiments and simulations where complicating elements are eliminated. The plastic response to steady-state shear forces in the lattice phase of matter is now open to further study and understanding. Dynamic experiments have observed the melting transition and liquid phase of vortex matter in the Corbino geometry^{3,4}, enabling new questions to be asked about thermodynamic phase transitions in the presence of inhomogeneous driving forces. And there is a whole additional phase of vortex matter, the glassy states, that are just beginning to be investigated in Corbino geometries⁶. Random pinning introduces a new dimension to shear phenomena, providing a competing mechanism for plastic response. The interplay of driving forces, shear gradients, and random pinning in vortex matter promises to substantially enrich our knowledge of plastic motion in all materials.

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