COMMENTARY

Pushing the limits for the highest critical currents in superconductors

Leonardo Civale

The word “superconductor” (SC) evokes the best-known and most-impressive characteristic of these materials, namely their capability to transport electrical current without dissipation. Zero resistance, though, is not the most fundamental property of an SC and by no means has a trivial explanation. The defining phenomenon in an SC is the Meissner effect, which dictates that, in the presence of a low external magnetic field (H), the field inside the SC is zero (1). The Meissner effect implies that if H is high enough the SC phase will be destroyed, i.e., there is a critical field. At intermediate fields, a broad variety of SCs, called “type II,” let most of the field penetrate in the form of “vortices,” while most of the material remains superconducting. This trick allows the critical field to reach dramatically higher values, making these materials technologically useful (1, 2). But there is one problem: In a homogeneous SC, electric currents move the vortices, producing dissipation (resistance R ≠ 0). This technologically detrimental motion can be precluded by the presence of material disorder, which produces “pinning centers” that trap the vortices, as long as the current density does not exceed a critical value, Jc (1–3). For five decades, the art and science of improving vortex pinning in SCs has progressed through educated guesses, theoretical modeling, and resource-intensive experimental optimization. Recently, enabled by more powerful computational capabilities and inspired by the “materials by design” paradigm, an effort to advance toward a systematic “critical-currents-by-design” approach has been underway (4). In PNAS, Sadovskyy et al. (5) continue moving on that path but incorporate a radically different strategy. Starting from a “seed” pinning landscape, they apply a genetic algorithm to allow it to evolve toward a configuration with optimum Jc. By informing the engineering of the pinning landscape, this design tool may significantly reduce the experimental trial-and-error burden.

Superconducting vortices are fascinating nanoscale objects, each one carrying one magnetic flux quantum. They are tubes of currents whirling around a central core, analogous to tomatoes and vortices in liquids. In the SC, the “fluid” is the Cooper pairs of electrons that perform the nondissipative transport and which, being electrically charged, generate the vortex axial magnetic field. At the central core, the superconductivity is destroyed, and it is only in these tiny filaments where dissipation occurs when vortices move. Vortices repel each other. In a homogeneous SC, this results in a textbook-simple equilibrium configuration: the triangular Abrikosov lattice of straight parallel vortices, with a lattice parameter that decreases as H increases (1). But vortices are elastic; they can bend and entangle. They do that to allow portions of their cores to go through nonsuperconducting regions of the material (defects) so that their energy decreases (1–3). The interaction between one vortex and one defect is already a complex problem involving several parameters. But the real difficulty is that the lowest energy (strongest pinned) configurations are the result of the tradeoff of many vortices interacting simultaneously with many defects and with each other (3). The general optimization problem of determining the pinning landscape that produces the highest Jc for arbitrary temperature (T) and H is unsolved, and the answer to the related question of what is the highest Jc that can be achieved for given T-H is unknown. The study by Sadovskyy et al. (5) proposes a different approach: Let evolution find out. There are at least three attractive concepts involved in the method. First, it does not assume any a priori pinning model. Second, it may produce arbitrary combinations of defects. Third, it can be run starting from different seed pinning landscapes.

Several successful pinning models have been developed. They typically describe the effects of one type of disorder and can be broadly divided into strong and weak pinning. Conceptually, perhaps the simplest case is an array of parallel columnar defects (CDs), as discussed by Nelson and Vinokur (6). This is the best-known example of strong pinning. The CDs are very efficient when H is parallel to them, simply because they can pin long portions of the cores. At

Materials Physics and Applications Division, Los Alamos National Laboratory, Los Alamos, NM 87545

Author contributions: L.C. wrote the paper.

The author declares no conflict of interest.

This open access article is distributed under Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND).

See companion article on page 10291.

Published online May 13, 2019.

www.pnas.org/cgi/doi/10.1073/pnas.1905568116
low vortex density (low $H$), a simple “one vortex, one defect” analysis is useful, but at high $H$ and/or high $T$, the problem is collective, with bundles of vortices pinned by many CDs. The other limit is a very large density of randomly distributed small defects (e.g., point defects). In this situation, the pinning is always weak and collective, arising from statistical fluctuations of the defects’ density. First developed by Larkin and Ovchinnikov (7) in the 1970s, these ideas were revised and expanded in the 1990s (3) as they were applied to describe pinning by point defects (such as oxygen vacancies) in oxide high-temperature SCs (HTSs). More recently, large attention has focused on randomly distributed larger defects, generically called nanoparticles (NPs) (8–10). Their popularity comes from the fact that they produce strong pinning that is rather isotropic (in contrast to CDs) and are easy to introduce artificially by chemical methods at industrial scale (11–13).

It is difficult to model combinations of different types of defects. The key problem is that pinning is not additive. It is well established that the strong pinning in thin films and coated conductors of the oxide HTS YBa$_2$Cu$_3$O$_7$ (which has the highest $J_c$ of any known SC) is due to the presence of complex mixed pinning landscapes (12, 14) (Fig. 1), but a universal description is elusive. One advantage of the mixed landscapes is that different kinds of defects may have synergistic effects; for instance, the addition of NPs may preclude the propagation of low-energy depinning excitations characteristic of CDs (14). But there are also competing effects. In some $T$-$H$ regimes, NPs may disrupt pinning by planar stacking faults (13), point defects may diminish the effectiveness of CDs (15) and NPs (16), and so on.

Some subtleties of the pinning landscapes are hard to anticipate. For instance, when we initially introduced CDs in YBa$_2$Cu$_3$O$_7$ single crystals by irradiation with 600-MeV Sn heavy ions, we observed a huge $J_c$ enhancement (17). Transmission electron microscopy images showed that the amorphous tracks were slightly splayed (due to Rutherford scattering) and somewhat inhomogeneous in diameter along their lengths. Later, we used 1-GeV Au ions that produced more parallel and uniform CDs but were surprised to find out that the $J_c$ increase was significantly lower. The solution to the puzzle came from a theoretical study by Hwa and coworkers (18) who realized that the splay had the beneficial effect of arresting the propagation of double-kink depinning excitations. Studies by Tamegai and colleagues in Tokyo (19) have shown that splay in the CDs can produce a rich and, in some cases, nonintuitive variety of pinning characteristics. One advantage of the evolutionary scheme is that no model is assumed, so none of these interactions needs to be explicitly introduced. The starting point may resemble a uniform random distribution of NPs, but the system is free to evolve into other landscapes, including mixed ones.

The capability of the scheme by Sadovskyy et al. (5) to start with an arbitrary seed landscape is also important because many defects appear spontaneously during fabrication (20). For instance, just in YBa$_2$Cu$_3$O$_7$, deposition methods that produce laminar growth (such as metal organic deposition) introduce planar stacking faults parallel to the $ab$ planes (13), as well as rather large RE$_2$Cu$_3$O$_5$ precipitates (12). Methods that produce columnar growth, such as pulsed laser deposition, produce linear dislocations (20). Point defects and twin boundaries are present in all cases. Polycrystalline SCs such as MgB$_2$ wires contain grain boundaries (21). Thus, any attempt to enhance $J_c$ by artificially incorporating defects in real SCs does not have the luxury to start from an empty space; preexisting defects with all their potential interplays (cooperative and competing) are unavoidable (11–16, 20, 22).

From a technological perspective, the most important question is, What is the highest achievable $J_c$, under given $T$-$H$ conditions? A simple calculation (3) suggests that, at low $T$ and low $H$, a CD could produce $J_c$ as high as the depairing current density $J_d$ (at which the Cooper pairs break), but experimentally, the maximum attained $J_c/J_d$ fraction is in the range of ~0.3 (20, 23). It is quite telling that the best $J_c/J_d$ fractions obtained by Sadovskyy et al. (5) are in the 0.3 to 0.4 range, even though there is nothing in the study pointing to the existence of a “hard barrier” at these values. Perhaps the conclusion is that this limit is just the result of vortices not being able to take full advantage of the available pinning due to the vortex-vortex repulsions. On the other hand, real pinning landscapes are more complex, and sometimes there is more than meets the eye. For instance, pinning associated with random NPs in YBa$_2$Cu$_3$O$_7$ is due in part to hard-to-visualize nanostrain in the matrix (24). Future developments of the evolutionary algorithm will certainly incorporate this type of subtlety. The problem is still open.

Acknowledgments
This work was supported by the US Department of Energy, Office of Basic Energy Sciences, Materials Sciences and Engineering Division.

Fig. 1. Transmission electron microscopy images showing examples of complex pinning landscapes in ReBa$_2$Cu$_3$O$_7$-coated conductors grown by different methods. (A) Metal organic deposition (MOD) with artificially added BaZrO$_3$ nanoparticles. Reprinted with permission from ref. 12. Copyright 2011 by the American Physical Society. (B) Pulsed laser deposition with artificially added self-assembled BaZrO$_3$ nanorods. Reprinted with permission from ref. 14. (C) MOD with artificially added Dy$_2$O$_3$ NPs and irradiated with oxygen ions. Reprinted from ref. 22, with the permission from AIP Publishing. For detailed descriptions of the figures, see the respective references.
1 M. Tinkham, Introduction to Superconductivity (McGraw-Hill, New York, NY, 1975).
2 A. M. Campbell, J. E. Evetts, Flux vortices and transport currents in type II superconductors. Adv. Phys. 21, 199–428 (1972).
3 G. Blatter, B. I. Ivlev, Quantum statistical mechanics of vortices in high-temperature superconductors. Phys. Rev. B Condens. Matter 50, 10272–10286 (1994).
4 I. A. Sadovskyy et al., Toward superconducting critical current by design. Adv. Mater. 28, 4593–4600 (2016).
5 I. A. Sadovskyy, A. E. Koshelev, W.-K. Kwok, U. Welp, A. Glatz, Targeted evolution of pinning landscapes for large superconducting critical currents. Proc. Natl. Acad. Sci. U.S.A. 116, 10291–10296 (2019).
6 D. R. Nelson, V. M. Vinokur, Boson localization and correlated pinning of superconducting vortex arrays. Phys. Rev. B Condens. Matter 48, 13060–13097 (1993).
7 A. I. Larkin, Y. N. Ovchinnikov, Pinning in type II superconductors. J. Low Temp. Phys. 34, 409–428 (1979).
8 C. J. van der Beek et al., Strong pinning in high-temperature superconducting films. Phys. Rev. B Condens. Matter Mater. Phys. 66, 024523 (2002).
9 A. E. Koshelev, A. B. Kolton, Theory and simulations on strong pinning of vortex lines by nanoparticles. Phys. Rev. B Condens. Matter Mater. Phys. 84, 104528 (2011).
10 R. Willa, A. E. Koshelev, I. A. Sadovskyy, A. Glatz, Strong-pinning regimes by spherical inclusions in anisotropic type-II superconductors. Supercond. Sci. Technol. 31, 014001 (2018).
11 J. Gutiérrez et al., Strong isotropic flux pinning in solution-derived YBa2Cu3O7-x nanocomposite superconductor films. Nat. Mater. 6, 367–373 (2007).
12 M. Miura et al., Mixed pinning landscape in nanoparticle-introduced YGdBa2Cu3O7 films grown by metal organic deposition. Phys. Rev. B Condens. Matter Mater. Phys. 83, 184519 (2011).
13 M. W. Rupich et al., Advances in second generation high temperature superconducting wire manufacturing and R&D at American Superconductor Corporation. Supercond. Sci. Technol. 23, 014015 (2010).
14 B. Maiorov et al., Synergetic combination of different types of defect to optimize pinning landscape using BaZrO3-doped YBa2Cu3O7. Nat. Mater. 8, 398–404 (2009).
15 B. Maiorov et al., Competition and cooperation of pinning by extrinsic point-like defects and intrinsic strong columnar defects in BaFe2As2 thin films. Phys. Rev. B Condens. Matter Mater. Phys. 86, 094513 (2012).
16 S. Eley et al., Decoupling and tuning competing effects of different types of defects on flux creep in irradiated YBa2Cu3O7-δ coated conductors. Supercond. Sci. Technol. 30, 015010 (2017).
17 L. Civale et al., Vortex confinement by columnar defects in YBa2Cu3O7 crystals: Enhanced pinning at high fields and temperatures. Phys. Rev. Lett. 67, 648–651 (1991).
18 T. Hwa, P. Le Doussal, D. R. Nelson, V. M. Vinokur, Flux pinning and forced vortex entanglement by splayed columnar defects. Phys. Rev. Lett. 71, 3545–3548 (1993).
19 A. Park, S. Pyon, T. Tamegai, T. Kambara, Flux pinning in Ba–xK–Fe2As2 superconductor with splayed columnar defects. Physica C 530, 58–61 (2016).
20 S. R. Foltyn et al., Materials science challenges for high-temperature superconducting wire. Nat. Mater. 6, 631–642 (2007).
21 D. C. Larbalestier et al., Strongly linked current flow in polycrystalline forms of the superconductor MgB2. Nature 410, 186–189 (2001).
22 M. Leroux et al., Rapid doubling of the critical current of YBa2Cu3O7-δ coated conductors for viable high-speed industrial processing. Appl. Phys. Lett. 107, 192601 (2015).
23 V. Selvamanickam et al., Critical current density above 15 MA cm2 at 30 K, 3 T in 2.2 μm thick heavily-doped (Gd,Y)Ba2Cu3O y superconductor tapes. Supercond. Sci. Technol. 28, 072002 (2015).
24 A. Llordes et al., Nanoscale strain-induced pair suppression as a vortex-pinning mechanism in high-temperature superconductors. Nat. Mater. 11, 329–336 (2012).