Energy Focus

Round-wire cuprate superconductors generate 33 Tesla magnetic fields

High-temperature superconductors (HTS) such as RE-$Ba_2Cu_3O_{7-x}$ (REBCO, where RE represents a rare-earth element) and $Bi_2Sr_2Ca_2Cu_3O_{10-x}$ (Bi-2223) are available only in rectangular tape forms, making it geometrically difficult to wind them into coils, especially for large magnets where multi-kiloamp conductors are needed. So low-temperature superconductors (LTS) such as Nb-Ti and Nb_3Sn, which can be formed as round wires, dominate the market for magnetic resonance imaging, nuclear magnetic resonance, and particle accelerator equipment. Now David C. Larbalestier of Florida State University (FSU), Christian Scheuerlein of the European Organization for Nuclear Research (CERN), and their colleagues have announced round, multifilamentary $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212) HTS wires with a very high critical current density of 2500 A mm^{-2} at 20 T and 4.2 K. These wires exceed a vital barrier that has restricted HTS rectangular tapes to a small subset of magnet applications. The fact that high current density can be obtained even when many high-angle grain boundaries (HAGBs) are present suggests an important change in the dominant paradigm of making these conductors.

"The initial excitement in the field of superconductivity always tends to be about discovering a higher transition temperature," said Larbalestier, the lead author of an article published in the April issue of *Nature Materials* (DOI: 10.1038/NMAT3887; p. 375). But applications cannot be satisfied by high T_c alone. It is necessary to have a high critical current density in a useful field and temperature range.

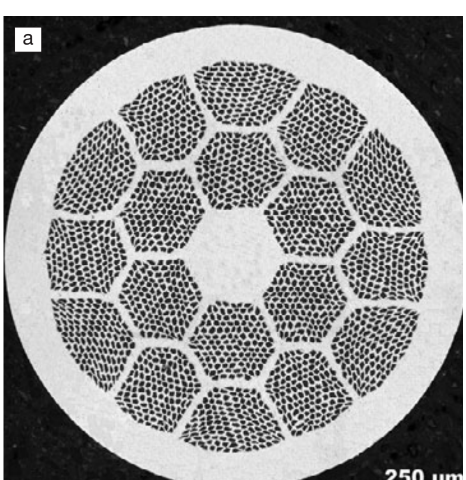
Bi-2212 was a neglected material when Larbalestier and Eric Hellstrom, both of the National High Magnetic Field Laboratory in the university, revived it about five years ago. Although it was the first HTS material to be considered for conductor use, it was quickly superseded by Bi-2223, with a 20 K higher T_c (110 K). Ultimately, the less anisotropic compound $YBa_2Cu_3O_x$ (YBCO) became the favored HTS. But Bi-2212 has one intriguing property: it can develop high critical current density in round and macroscopically untextured form—but only in very short wires, not in the lengths needed for magnets.

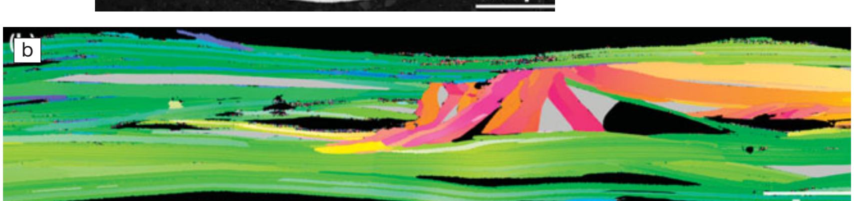
Larbalestier said, "We found that the critical problem was not the presence of many high-angle grain boundaries in the wire but rather lots of bubbles generated by residual gas," which form during processing of the Bi-2212 powder.

Until now, the commonly held theory for low critical current densities in HTS was that the presence of many HAGBs in the superconducting phase blocked the supercurrent. Hence, all processing was devoted to producing a highly textured superconducting phase, with a minimum of HAGBs, which required the tape form. Tape-form conductors of REBCO and Bi-2223 followed. The high-performing Bi-2212 wires produced by Larbalestier and his colleagues in the present work manage to keep the supercurrent flowing despite the presence of many HAGBs.

Gas bubbles are an inherent consequence of the need for powders to slide over one another during deformation. Sliding means that the terminal mass density of the powder inside its metallic sheath is only about two-thirds, with the remainder being gas, generally air. While bubbles of gas that formed voids in the superconducting phase had been seen before, especially in short tapes, they were considered to be a minor nuisance compared to the overwhelming effects of the HAGBs. Depending on how it was viewed, a bubble could be obscured by a bridging Bi-2212 crystallite, or filled by polishing debris in cross sections. Alternatively, the gas that forms the bubbles could diffuse out of the ends of unsealed short wires, thus eliminating the bubbles. All of this led to huge variability and generally very poor properties, especially in any length suitable for magnet wires.

At CERN, researchers were able to watch the heating sequence in real time. Larbalestier said, "As the 2212 filaments enter the melt stage, Christian Scheuerlein [at CERN] was able to see the formation of little lenses of gas and observe the growth of these lenses into bubbles. The critical parameter controlling the current density was thus seen to be the formation of these





(a) Cross sections of the round wire Bi-2212 multifilament conductor before reaction, and **(b)** electron backscatter diffraction images of the grain structure after reaction at a high current density state. Major misalignments shown by the red-colored grains exist without preventing high filament current densities. Credit: Jianyi Jiang and Fumitake Kametani.

https://doi.org/10.1557/mrs.2014.111 Published online by Cambridge University Press

gas bubbles which had to be bridged by 2212 grains that reformed during the solidification process."

So how to eliminate the formation of gas bubbles during the heating stage? Hellstrom and Larbalestier had met a variant of this problem earlier with Bi-2223 when they had noticed some residual porosity in samples of that material. Working with American Superconductor Corporation, they had jointly patented an overpressure process that closed up the small residual pores left after rolling the wire to tape, raising the current density by about 30%. Using this process, researchers Jianyi Jiang and Maxime Matras at FSU started reacting round, 0.8-mm-diameter Ag wires embedded with 666 Bi-2212 powder filaments, each 15 µm in diameter. Inserting this wire into an overpressure furnace at pressures of 1–100 bars during the heat-treating process prevented wire diameter expansion by Ag creep, allowing for the first full densification of the Bi-2212 phase. Measurement of the whole-conductor (or engineering) current density, J_E, revealed that J_E increased by a factor of eight going from 1 bar to 100 bars pressure. The overpressure collapsed bubbles as they formed, leading to higher critical current density.

The research team made a test coil that reached 33.8 T. Larbalestier said, "This is not just a breakthrough result for short wire samples—it's a breakthrough using long samples that have been tested in a very high field magnet. The wires are now being scaled up to kilometer lengths with the wire producer, Oxford Superconducting Technology."

The research team wants to repeat this process in YBCO next which, they said, would be genuinely revolutionary for superconducting magnet technology because it would allow construction of multi-Tesla magnets in the 30–70 K regime where no other superconductor can operate.

Tim Palucka

Bio Focus

Skin cancer probe applied to in-depth artwork investigation

A few years ago, W.S. Warren of Duke University (Durham, N.C.) saw an exhibit at the National Gallery in London on scientific methods for detecting art forgeries. "I walked through that exhibit, and at the end of that time realized that the technologies that were being used were the technologies of 30 to 40 years ago. And asked what would happen if we started using modern bioimaging technologies in this particular application," Warren said.

Warren's group at Duke University works on biomedical imaging techniques, where they have applied the pump-probe microscopy technique to provide high-resolution images of biological pigments in skin cancer research. Pump-probe microscopy is a nonlinear technique in which the signal intensity is proportional to the product of the intensities of two lasers, and less affected by light scattering. Using near-infrared wavelengths, skin can be probed to ~1 cm depth.

As reported in the February 4 issue of *PNAS* (DOI: 10.1073/pnas.1317230111; p. 1708), Tana Villafana demonstrated the feasibility of the pump-probe microscopy technique to detect forged paintings using mock paintings; this technique was used to investigate specific pigments in a 14th-century painting. Villafana is a graduate student in Warren's team and worked in collaboration with the North Carolina Museum of Art and the Washington National Gallery of Art.

There is actually a great deal of similarity between imaging skin and imaging a painting. Warren said, "There are many layers of painting and the layers are designed to replicate the refraction and scattering that you have at normal skin; that's what makes it look realistic. For example, Da Vinci, when he painted the Mona Lisa, put 40 layers of paint on the face." Therefore, he said, the issues associated with attempts to image through skin to detect cancer are the same when trying to figure out the various layers in paint.

What makes analysis of paint more complicated than skin is that skin has only a few different kinds of pigments—while the different kinds of pigments in a painting are limited only by the artist's imagination. To cope with the larger range of molecular pigments, an increased spectral range of pump and probe wavelengths was used. Furthermore, based on what is known about the palette used, for example, by renaissance painters, a library of different pigments was created that produce very different signals as a function of the pump-probe delay.

The great advantage of the technique is its nondestructive character. "The conventional method is to take a scalpel to the painting, take out a tiny chip, and do microscopy on that chip. So obviously that's destructive and obviously the sampling that you do is very incomplete," said Warren.

Jennifer Mass, senior scientist and adjunct professor at the Winterthur/University of Delaware Program in Art Conservation, welcomes the advent of this new technique. "Nondestructive analysis is commonly applied to the characterization of works of art, but nondestructive depth profiling is a particular challenge for the field. Femtosecond pump-probe microscopy is a welcome addition to our arsenal for investigating the structure, authenticity, technology of manufacture, and state of preservation of works of art."

The investigation of paintings is just a start. With a three-year grant from the US National Science Foundation, Warren's team will carry out further research on artwork exploration. One of the next subjects is the investigation of old pottery, where the signal from the iron oxide used for coloring can be used to image temperatures for glaze firing. While biomedical applications remain the main focus of his laboratory, Warren sees the work relating to art as a nice spin-off of biomedical research investment to benefit society in another way.

Dirk Wouters

https://doi.org/10.1557/mrs.2014.111 Published online by Cambridge University Press