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VIEWPOINT

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Viewpoint

A new scaling approach and quantitative angular critical current measurement using magnetization

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(Some figures may appear in colour only in the online journal)

This is a viewpoint on the fast track communication by Mishev *et al* (2015 *Supercond. Sci. Technol.* **28** 102001)

> ‘One scaling to rule them all, one scaling to find them…’ adaptation from J R R Tolkien.

Scaling fascinates physicists as one of the tools where we distill the essence of a problem and find hidden relationships and universalities among dissimilar problems. The paper by Mishev *et al* [1] is one of these occasions when a scaling rule is proposed for a highly relevant problem: in this case, vortex pinning. The manuscript also describes a method that allows extraction of better quantitative values of the angular dependent critical current density (J_c) measured by magnetization. They perform all this in a carefully controlled experiment starting from a clean Co-doped $BaFe_2As_2$ (Ba122) single crystal that is irradiated with neutrons to create nano-sized defects.

The problem of understanding the critical current is a complex one [2]. It deals with a variable number of elastic objects (vortices) interacting with each other to achieve an ordered lattice and also interacting with several types of pinning centers that in the majority of cases drive the lattice towards a disordered state. Pinning centers are of many different kinds, such as point defects, columns, planes and nanoparticles. There are good theoretical foundations for point and correlated defects from which we experimentalists can draw to analyze our results and eventually continue improving superconductors [2]. But such descriptions are less developed for the pinning originating from nanoparticles, although it has been clear since the seminar work by Driscoll *et al* that this is a good method to achieve high J_c [3]. Having a scaling rule to analyze nanoparticle contributions will undoubtedly help in gaining a better understanding of their contribution toward higher J_c.

Angular dependence has been extremely useful in identifying the contribution of different defects to the critical current [4, 5]. Following the work done studying vortex solid–liquid transitions [2, 6, 7], anisotropic scaling analysis was performed on J_c angular dependences. This analysis showed that for PLD YBCO thin films, point-defects contribute greatly to J_c (see for example, figure 1) in a wide angular range. The region of contribution was found by showing that large parts of $J_c(\Theta)$ scaled if plotted as a function of $\varepsilon(\Theta)\,H$, with $\varepsilon(\Theta) = [\cos(\Theta)^2 + \sin(\Theta)^2/\gamma^2]^{1/2}$, where Θ is the angle from the c axis and γ is the electronic mass anisotropy, with $\gamma \sim 5$ for YBCO thin films. On top of this anisotropic J_c background, the contribution of different correlated defects can be clearly seen in figure 1. This scaling is successful because the pinning is by point-like defects that are randomly dispersed (not correlated). It is clearly not valid for correlated defects, such as can be seen by deviation from the fit for the peaks near **H**||c and **H**||ab.

Similar to that of correlated defects, the nanoparticle contribution cannot be accounted for by anisotropic scaling; although in some cases scaling with an

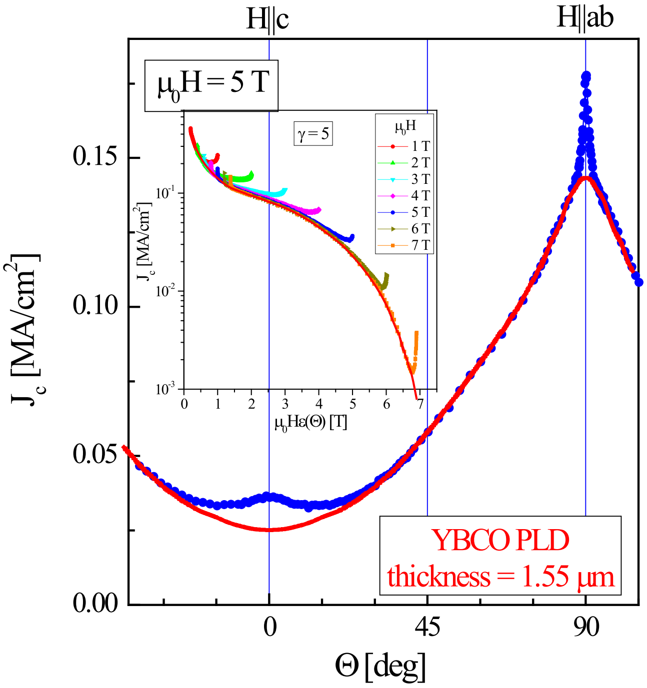

Figure 1. J_c versus Θ at $\mu_0 H = 5$ T. The red line is the scaled J_c using the anisotropic scaling shown in the insert [5].

'effective γ' was obtained [8]. The lack of anisotropic scaling was evident in a variety of samples with nanoparticles, such as BZO nanoparticles in MOD YBCO [9], or systems like HLPE with different oxide precipitates [10], seen in angular dependence of both J_c and the glass transition [11]. The effect of nanoparticles is not always easy to detect, because the angular dependence in YBCO is very complex. Starting along the ab planes, the effect of nanoparticles is seen by a fairly fast growth near ab, to be almost flat around the *c* axis, in an inversed anisotropy-like fashion. However, until now this feature has not been described quantitatively or a scaling proposed. Van der Beek *et al* also showed that spherical pinning centers give rise to an anisotropic contribution that is a maximum along the *c* axis [12]. It is important not to confuse this maximum with the peak from correlated defects. The former is a manifestation of the anisotropic nature of the materials and the latter vortex localization along the correlated defects' direction, although the description of short columns should take into account both phenomena. Koshelev and Kolton find a similar angular result but derive it from a model that uses vortex cutting as the mechanism that determines J_c [13].

In order to study only the contributions of nanosized defects, the Vienna group used a clean single crystal of Co-doped Ba122 and produced nanosized defects by neutron irradiation. Typically, an experiment on a single crystal allows for a much better control of the pinning centers that are being added, as well as a 'before' and 'after' comparison. No crystal is defect free, but the increase obtained by irradiation can be as large as several orders of magnitude. In the case of Mitshev *et al* [1], they started from a single crystal of Ba122 with $J_c(sf) \sim 16 \times 10^8$ A m^{-2}, and irradiated it with neutrons that create perfect defect size defects increasing J_c a factor of four at low fields. Although Ba122 is a two band superconductor, the lack of intrinsic pinning and other sources of strong or correlated defects allow Ba122 single crystals to be a good model system.

Once the desired pinning landscape was obtained, the Vienna group tackled the problem of measuring its angular properties. Most angular dependent critical current experiments have been done using transport, as it allows exploring the full angular range. However in certain cases, as in bulk (polycrystalline or single-crystal) samples, the sheer amount of current required often make the measurements impossible.

Thus, magnetization has been proven essential to study vortex pinning in single crystals, using the critical state model. However, extracting the critical current from angular dependent magnetization measurements is not straightforward, as the current is not applied solely in one direction but flows around the sample. So, when the magnetic field is applied away from the normal to the sample, there is always a component of the current that is not in the maximum Lorentz force configuration ($\mathbf{J} \perp \mathbf{H}$). This problem has been dealt with by reducing the sample dimensions along the variable Lorentz force direction, either by introducing cuts in thin films or selecting/cutting crystals with a narrow dimension [14, 15]. The Vienna group has a long standing experience in the angular dependence of magnetization, and they are developing a method that will allow other groups to improve the quantification of the critical current experiments.

The sample and measuring systems allow Mishev *et al* to show that instead of the standard anisotropic scaling, the $J_c(\theta)$ could be scaled using $J_c(\theta)/\varepsilon(\theta)$ versus $\varepsilon(\theta)H$. The scaling obtained at 15 K is very good, and I expect that this result will prompt researchers to test this newly proposed scaling analysis in a variety of systems and conditions.

Summarizing, improvements in the angular dependent magnetization measurement of J_c allowed the testing (at a single temperature) of a proposed new scaling, where not only the field is scaled by the anisotropy, but J_c is inversely scaled, such that if J_c is governed by nanosized defects, a region of scaling will be found if $J_c(\theta)/\varepsilon(\theta)$ versus $\varepsilon(\theta)H$ is plotted. By performing this scaling the authors take into account the extra effect of the anisotropy.

Acknowledgments

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