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Measurement of transverse J_c profiles of coated conductors using a magnetic knife of permanent magnets

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The transverse J_c distribution in YBCO coated conductors was measured non-destructively with high resolution using a ‘magnetic knife’ made of permanent magnets. The method utilizes the strong depression of J_c in applied magnetic fields. A narrow region of low (including zero) magnetic field, in a surrounding higher field, is moved transversely across the sample in order to reveal the critical-current density distribution. The net resolution of this device is approximately 65 μm , and the J_c resolution is better than 0.5 %. A Fourier series inversion process was used to determine the transverse J_c distribution in the sample. The J_c profile was correlated with other sample properties of coated conductors prepared by pulsed laser deposition. Because of its straight-forward and inexpensive design, this J_c imaging technique can be a powerful tool for quality control in coated-conductor production.

We describe a novel imaging device which tests the transverse critical-current uniformity in superconducting tapes. High-temperature superconducting (HTS) tapes, based on $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO), are prepared on textured metallic substrates. The quality of these films with respect to their current-carrying capability, especially in applied magnetic fields, has increased steadily over the years due to a continuous world-wide effort to develop commercial HTS applications. Self-field J_c values of over 500 A per cm width at 77 K, and conductor lengths of near-km length have been achieved [1,2]. In addition, tape widths have also expanded to 10 cm. For the production of high-quality coated conductors, not only the longitudinal [3] but also the transverse homogeneity in J_c is essential. This is especially true with respect to desired striations for AC applications to reduce hysteresis losses [4,5]. It is also important for assuring a continuing high and uniform current-carrying capability over length for the production of long coated conductors by providing immediate feedback to control production parameters.

There is a variety of methods for determining the J_c distribution in superconducting thin films, such as magneto-optics [6], magneto scan [7], laser scanning [8,9] or patterning individual bridges [10]. All of these methods are either destructive or slow and, therefore, are not suited to monitor tapes for quality control.

We show measurements of the transverse J_c distribution of coated conductor samples, using a straight-forward and inexpensive design, where the magnetic field was generated by $\text{Nd}_2\text{Fe}_{14}\text{B}$ permanent magnets. $\text{Nd}_2\text{Fe}_{14}\text{B}$ is a hard-magnetic material with a saturation magnetization of about 1.4 T. The magnetic field at the surface of commercial $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets of cm dimensions is typically 300 mT. Two magnets in close proximity develop fields of order 600 mT. Such a field can suppress J_c outside the knife region by a factor 5.

We confirmed by cryogenic Hall probe measurements that the spin-reorientation at 135 K [12], i.e. the opening of a spin cone around the easy axis with an angle of up to 30° , does not result in a change in the direction of the magnetic field between two $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets. The magnitude of the field changes by less than 4 % between 75 K and room temperature.

The concept of the magnetic knife was first introduced by ten Haken *et al.* [11] using electromagnets. The magnetic knife utilizes the strong $J_c(B)$ dependence in HTS when the field is applied parallel to the crystallographic c -axis and tape normal. The magnets are arranged around the tape in such a way that in the transverse direction the magnetic field in the plane of the sample changes sign. The magnetic field has to go through a line of zero field, shown in Fig. 1a. This transition region takes the magnetic field from around -600 mT through zero to around +600 mT and is scanned transversely across the sample. The magnetic knife is shown in Fig. 1b. The four magnets are held in a G10 holder, and each has the dimensions $5 \text{ mm} \times 5 \text{ mm} \times 20 \text{ mm}$, which is well suited for tapes up to 10 mm wide. The vertical spacing (in z direction), v , is around 0.5 mm, the horizontal spacing in y direction, h , can be varied between 0 mm and 2 mm, depending on the desired resolution. We have found that zero spacing gives the best results. The device is used by measuring the critical current for a certain position of the magnetic knife on the tape, using a low-voltage, four-point technique. The knife is moved across the tape by a screw thread of 3 mm diameter (1 turn equals 0.5 mm movement), providing a positional accuracy of the order of $10 \text{ }\mu\text{m}$. Current was applied through Cu press contacts, and voltage taps were soldered. The critical current I_c is determined by a voltage criterion of

1 μV . By assuring a voltage noise level of about 20 nV and eliminating thermal voltage offset of similar magnitude, an I_c uncertainty of around 0.5 % was achieved.

Figure 2 shows the magnetic-field profile of the device in the plane of the sample, measured at room temperature with a Hall sensor of 100 μm diameter. It shows a continuous increase of B from -600 mT to +600 mT in a zone of 1.3 mm in width. That is comparable to the magnetic knife based on electromagnets [13]. In contrast, the profile with permanent magnets shows features outside the knife zone, due to the internal magnetic structure of the magnets. This additional structure was taken into account in our inversion process described below. Figure 2 (Inset I) shows a typical $I_c(B)$ dependence of a pulsed laser deposited coated-conductor sample. In fields up to 1 T, this dependence is usually described as a power law [14, 15] $I_c \propto B^{-\alpha}$. The parameter α for the data shown here is 0.37. Below 100 mT at 75 K, the dependence can be described as a logarithmic decrease $I_c \propto \ln(B/B^*)$, where B^* is a fitting parameter related to the accommodation field [16]. The best fit in the range of interest for our purpose, i.e. combining these two regions, is a modification of Kim's model [17]:

$$I_c(B) = I_c(0) \cdot (1 + |B/B_0|^\beta)^{-\alpha/\beta} \quad (1)$$

with B_0 , α and β being fitting parameters. B_0 is comparable to, but typically larger than, B^* . The overall fit was accurate to about 0.2%. Figure 2 (Inset II) shows the resulting convolution function g :

$$g(y) = I_c(B) \cdot B(y) \quad (2)$$

for the data of Inset I. The peak (i.e. the knife zone) has a FWHM of 130 μm .

For the deconvolution process we have chosen a Fourier series inversion. The unit cell was doubled by mirroring the raw data at one sample edge. We used a grid of 315

points in total and considered Fourier terms up to the 100th order. This truncation allows less resolution than the Nyquist criterion. In order not to mix noise features into the deconvolved data, the Fourier terms were multiplied by a low-pass soft filter term $\exp(-\tau G^2)$, where G is $2\pi n/l$, n is the term order and $l = 20$ mm the width of the supercell (or twice the tape width). The parameter τ is set at that point where the size of the Fourier series is equal in amplitude to the experimental noise. The net resolution of the magnetic knife is 65 μm .

Figure 3a shows the I_c data of a PLD coated-conductor sample of 10 mm width [18], measured with the magnetic knife using a step size of 125 μm . The slight difference in the background between the right and the left side is due to an off-axis magnetization in the permanent magnets as well as slight differences in the vertical separation distance. The same behavior is seen in the field profile and the convolution function. Hence, this asymmetrical offset is completely compensated for in our deconvolution process to the 0.1 % level. The deconvolved curve for these data is shown in Fig. 3b, scaled in I_c per cm width (I_c^*). We see that deconvolution essentially enhances and sharpens the features in the data, the rounding in the I_c data being due to the finite width of the knife, e.g. I_c values above the background level outside the tape region. The cut-off prevents unwarranted sharpening of data features and prevents the effect of noise amplification. Furthermore, the data reveal that the sample is homogeneous to within 10 %, although I_c^* exhibits several places of lower I_c^* and a slight maximum around 3 mm.

Figure 4 shows a comparison between the magnetic knife I_c^* profile (Fig. 4a) and structural data measured by x-ray diffraction (XRD) (b-c), thickness (d) as well as the J_c data of individual filaments (e) as a function of transversal tape position y . The filaments

have been patterned mechanically and are clearly identifiable when the striated sample is measured with the magnetic knife, shown in Fig. 4f for three different positions 2 mm apart. The profiles of Figs. 3 and 4a were measured at position m. The cuts are not resolved completely because a lower spatial resolution (step size 250 μm) was used. Each cut leads to a reduction of around 1% of superconducting cross section, as was determined by J_c measurements of the whole sample with and without applied magnetic field, before and after the striation. J_c of the individual filaments was measured differentially by successive blocking current flow through the filaments. X-ray diffraction data (minimum in $\Delta\phi$, maximum in (103) amount) and the thickness profile of the superconducting filaments suggest that the laser plume center was shifted around 2 mm to the left from the center of the tape. That can explain the higher J_c^* values at the left side of the tape. Furthermore, also the highest filament J_c value was measured left of the tape center. J_c^* falls to zero at the tape edges in a region of around 0.5 mm. The reason for this rather broad region might be an inferior microstructure (FWHM of the in-plane texture increases and YBCO (00l) peak intensities decrease), compared to the rest of the tape. The current density has to be zero exactly at the location of the sample edge in order to avoid singularities. It is apparent that the J_c^* profile shows much finer features than are visible with x-ray diffraction. XRD is, hence, less preferable for quality control of sub-millimeter filaments than the magnetic knife. Whereas the J_c^* profile shows the highest values at the left side of the tape, this region shows lower J_c values when the individual filaments are measured in a homogeneous field of 600 mT. The low J_c values could be due to a low- J_c region outside the magnetic knife. The filaments were cut over a length of 9 mm, which is much longer than the length of the magnetic field of the knife (3–4 mm). A low- J_c region at the

right side of the tape, marked by an arrow in Fig. 4, re-appears in the magnetic-knife measurements of the striated sample but not in the I_c measurements on the individual filaments, possibly for the same reason. The left most cut is not fully developed at positions m and l.

The samples investigated show a relatively high overall homogeneity. However, there are finer features which can be well correlated to growth-related sample properties. These data show that the magnetic knife can provide more information than XRD measurements or I_c measurements on individual filaments alone. In summary, because of its straightforward and inexpensive design, this J_c imaging technique can be a powerful tool for quality control in coated-conductor production.

Figure 1: a) Schematic arrangement of the permanent magnets around the superconducting tape and the field profile in the plane of the tape (thin grey inset). b) The magnetic knife with tape sample. The tape is the silver-coated ribbon. The magnets in their holders are cut and reversed left to right to form the knife.

Figure 2: The transverse magnetic field profile $B(y)$ across the tape, measured with a Hall sensor of 100 μm diameter at room temperature. Inset I: Typical $I_c(B)$ dependence of a coated-conductor sample. Inset II: Convolution function $g(y)$ for the data of inset I.

Figure 3: a) The I_c data of a PLD coated conductor sample of 10 mm width, measured with the magnetic knife using a step size of 250 μm . b) Deconvolution of data from a), scaled to I_c per cm width. The deconvolved data b) show enhancement of smaller features seen in a).

Figure 4: Comparison of the a) I_c^* profile, measured using the magnetic knife, with structural data (b) in-plane FWHM, c) amount of (103) orientation), d) film thickness as well

as e) J_c data measured on individual filaments as a function of transversal tape position. Fig. 4f shows magnetic knife data of the striated sample on three positions *right*, *middle*, *left*, each 2 mm apart (m being position of Fig. 4a, data of m and l shifted for clarity). The dotted lines are parabolic fits used as guides for the eye.

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