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Asymmetric angular dependence of J_c in coated conductors prior to and after fast neutron irradiation

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ABSTRACT

Angular dependent measurements of J_c were performed on a commercial coated conductor (SuperPower) consisting of a 1 μm thick YBCO layer grown on a MgO IBAD buffer layer. An asymmetric behavior of the angular dependence of J_c ($J_c(\Phi)$) was found with a changing distance between the two peaks at different temperatures and applied magnetic fields. One peak always occurs when the field is oriented parallel to the tape surface, the other smaller peak is located in the perpendicular orientation at high fields, but slightly shifted (by up to 10°) at 77 K and low magnetic fields. This peak shift, the overall $J_c(\Phi)$ asymmetry and the influence of fast neutron irradiation on $J_c(\Phi)$ are discussed. The spherical defects, introduced by collisions of fast neutrons with the lattice atoms, are randomly distributed, add to the as-grown defect structure and change the critical current anisotropy by altering both peaks.

1. Introduction

The fabrication of coated conductors (CC) significantly improved during the last years. Recently, the first HTS devices (coils and cables) were put into operation. The lengths of CC increased up to around one kilometer and the critical currents are higher and more uniform over the whole length of the conductors. (In 2008 the longest wire length of 1311 m was produced by SuperPower with a minimum I_c of 153 A [1].) It is very important for future applications of coated conductors to obtain high critical currents at all orientations of the magnetic field, because the intrinsic anisotropy of YBCO is a considerable complication for the design of HTS devices. It is therefore a challenge to reduce the strong anisotropy of YBCO CC. In addition, the excellent performance for $H \parallel ab$ field should not be degraded. We present a comparative study of the angular dependent critical current densities in commercial YBCO CC before and after irradiation with fast neutrons. We will show that the asymmetric behavior of $J_c(\Phi)$ is very similar to results on thin films, where the *ab* planes were tilted with respect to the sample surface. The position of the maxima in the two main field orientations and their changes as well as changes in the overall symmetry of $J_c(\Phi)$ after irradiation to different fast neutron fluences will be also discussed.

2. Experimental

Our commercially available samples, state-of-the-art coated conductor from SuperPower, are based on an IBAD MgO template with the YBCO layer made by metal organic chemical vapor deposition (MOCVD). They were characterized before irradiation and then sequentially irradiated to fast neutron fluences of $4 \times 10^{21}\ \mathrm{m^{-2}}$ and $1 \times 10^{22}\ \mathrm{m^{-2}}$. The tapes are 4 mm wide, the thickness of the YBCO layer is 1 μm, and they are completely coated with a copper stabilizer. The transport measurements were made on approximately 26 mm long pieces by the standard four-probe technique with a voltage criterion of 1 μV/cm. The sample was rotated in magnetic fields of up to 6 T under the maximum Lorentz force configuration. A helium flow gas cryostat with a split coil and a rotating sample holder were used for our experiments. This setup allows us to measure $J_c(\Phi)$'s at variable temperatures and currents of up to 150 A. Some of our initial measurements were made in a setup based on a 1.4 T electromagnet with liquid nitrogen as a coolant. The irradiation was made in the central irradiation facility of the TRIGA MARK II research reactor in Vienna at a power of 250 kW. The temperature during irradiation did not exceed 60 °C. The type of artificial defect induced by neutron irradiation strongly depends on the kinetic energy of neutrons. High energy neutrons produce spherical defects of amorphous material with a diameter of a few nm (so called collision cascades), point defects and clusters of point defects are created also by neutrons with lower energies [2]. All fluences refer to fast neutrons with energies $E_n > 0.1$ MeV. The samples were irradiated sequential by, first step to a fluence of $4 \times 10^{21}\ \mathrm{m^{-2}}$, then remeasured, and then irradiated again to a fluence of $1 \times 10^{22}\ \mathrm{m^{-2}}$.

3. Results and discussion

The angular dependence of the critical current density $J_c(\Phi)$ at 77 K and 700 m T is shown in Fig. 1, where two peaks are observed.

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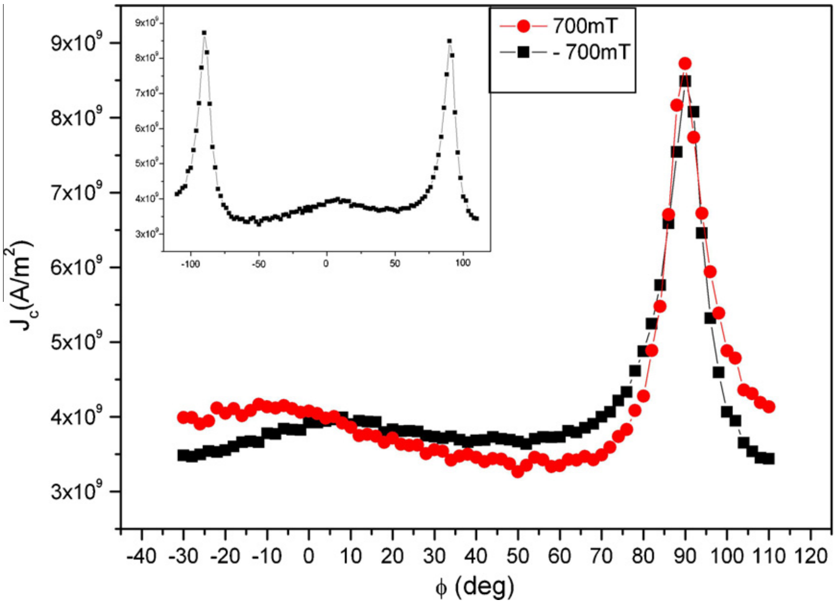

Fig. 1. Angular dependence of $J_c(\Phi)$. The angular scale refers to the sample surface. The tape was measured twice, once in a field of 700 m T and then in the reversed field. The insert represents both measurements on a single angular scale covering ≈240°.

The first is the *ab peak* at $\Phi = 90^\circ (90^\circ \iff H \parallel$ sample surface) and the other less pronounced is located at an interval $\Phi \approx \langle -20^\circ, 20^\circ \rangle (0^\circ \iff H \perp$ sample surface) – the *second peak*. Both of them have an asymmetric shape and the overall $J_c(\Phi)$ follows a $J_c(\Phi) = J_c(\Phi + 180^\circ)$ periodicity, but not a $J_c(\Phi) = J_c(-\Phi)$ symmetry. The broken symmetry of $J_c(\Phi)$ implies the existence of some geometrical effects and/or the presence of correlated pinning centers, which are not aligned with the main crystallographic directions [3]. Asymmetric $J_c(\Phi)$'s were often reported [3–6], e.g. by Maiorov et al., who cut two different bridges into the same tape [3]. The *ab* planes were tilted from the sample surface by an angle Ψ in y orientation (Fig. 2). One bridge was cut in y and the other in x orientation. Although both bridges were measured, the $J_c(\Phi)$ asymmetry was found only in one bridge, namely that cut in x orientation. The other bridge showed a symmetric $J_c(\Phi)$ and lower absolute values of J_c. Wang [4] also observed an asymmetric $J_c(\Phi)$ curve similar to ours in thin films with tilted *ab* planes. Common to all those measurements was the fact, that the *ab peak* was not observed at $\Phi = 90^\circ$, but at a different angle $\Phi = (90^\circ - \Psi)$. At high magnetic fields the peak was positioned precisely at $\Phi = (90^\circ - \Psi)$ and shifted to lower angles with decreasing field. A possible explanation of this *ab peak* shift was given by Silhanek et al. [7] as being caused by a misalignment between the externally applied magnetic field H and the internal field B. Granularity effects [8,9] were discussed as well. However, we did not observe any change in the position of the *ab peak* within the accuracy of our experimental setup (±0.5°). High resolution $J_c(\Phi)$ measurements were done (Fig. 3) with a sensitive Hall probe to determine the magnetic field orientation with maximal accuracy. (The Hall probe was tested for offset voltage and linearity at different temperatures.) The magnetic field orientation was calculated from the Hall voltage using: $\Phi = a\cos(U_{\mathrm{Hall}}/U_{\mathrm{Hmax}})$. As shown in Fig. 3, no shift of the *ab peak* is found at any field and temperature. These measurements were done with a 0.5° resolution and all deviations of the *ab peak* absolute angular position are within accuracy of 0.5° + 1° (estimated misalignment between the Hall probe and the sample due to mounting $\leqslant 1^\circ$). Therefore, the *ab* planes are aligned parallel, or almost parallel to the sample surface [3,5], because the *ab peak* was always found, when the field was aligned parallel to the sample surface under our experimental conditions (B,T).

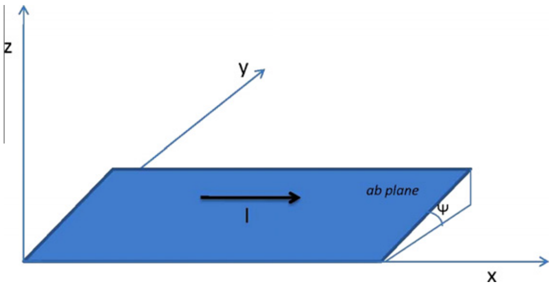

Fig. 2. Sketch of the *ab* planes tilted from the sample surface.

A different situation was found in the case of the *second peak*. This peak was fixed at the same position and rather symmetric at lower temperatures (64 K, 50 K), where the magnetic field was always above 3 T. According to the Hall probe its position was always exactly perpendicular to the sample surface (±0.5° due to the angular resolution) in these measurements. However, at 77 K the *second peak* is strongly asymmetric and its maximum occurs out of the tape normal ($\Phi = 0^\circ$), e.g. at $\Phi = -5^\circ$ at 1 T. At lower fields (Fig. 1) the peak shifts even more, but at high fields it almost aligns ($\Phi = 0^\circ$), e.g. 5 T, as well as at lower temperatures. One reason for the angular variation of $J_c(\Phi)$ is the electronic mass anisotropy of YBCO. A useful approach to describe this effect is the anisotropic scaling approach by Blatter et al. [10]. Accordingly J_c systematically increases with Φ, if pinning is only due to random defects. The *second peak* cannot be described by this model, except by assuming correlated pinning. Natural candidates for c-axis correlated pinning centers are twin planes [11–13] or edge and screw dislocations [14,15]. The *second peak* probably results from a combination of them [16].

The asymmetric $J_c(\Phi)$ behavior and the shift of the *second peak* in a tape, in which the YBCO planes do not break the symmetry, remain an open issue. Possible candidates for this effect are the Lorentz force acting on the tape during the measurement, differing barriers to surface entry for flux lines at the two interfaces [17] or correlated pinning centers, which are not oriented perpendicular to the tape surface and which are dominant only at certain

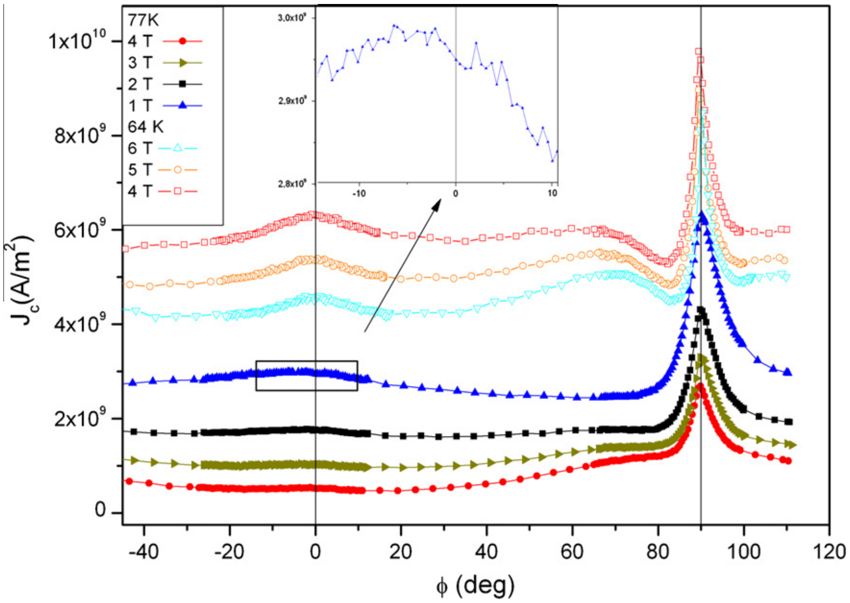

Fig. 3. $J_c(\Phi)$ at 77 K and 64 K in fields up to 6 T.

fields and temperatures. None of these effects can be completely excluded. The Lorentz force on the tape during the measurement may cause the difference of the $J_c(\Phi)$'s at reversed magnetic fields, since the tape is either pressed towards the sample holder and or into the opposite direction. This could strain the tape differently and lead to the observed behavior of $J_c(\Phi)$. However, many measurements using the same setup and the same sample holder, leading to the same mechanical loads, were done on different CC and no asymmetry has been observed [18].

Differing surface barriers causing asymmetric $J_c(\Phi)$'s were observed in PLD thin films [17]. However, this mechanism was found only in PLD films up to now and the most important outcome was a significant difference in J_c upon reversing the current (or field), which is not observed in our case (Fig. 1).

The last option is rather more general and based on changing pinning mechanisms at low magnetic fields as well as the loss of pinning efficiency due to thermal activation at high temperatures. The n-value is defined from the current–voltage curve in the transition region between thermally assisted flux flow and flux flow by a power law

$$E = E_c \left(\frac{I}{I_c} \right)^n,$$

where the n-value is the exponent n and E_c is the voltage criterion for I_c. The values of J_c and the n-values are not completely independent. Strong arguments for a functional dependence within one pinning regime were found by Civale et al. [19]. Indications for different pinning mechanisms are shown in Fig. 4, where the n-values of the $J_c(\Phi)$ measurements change behavior near $\Phi = 90°$.

We can exclude the above-mentioned explanation of the *ab peak* shift due to *H* and *B* competition, because the shift of the second peak should be more pronounced at low external magnetic

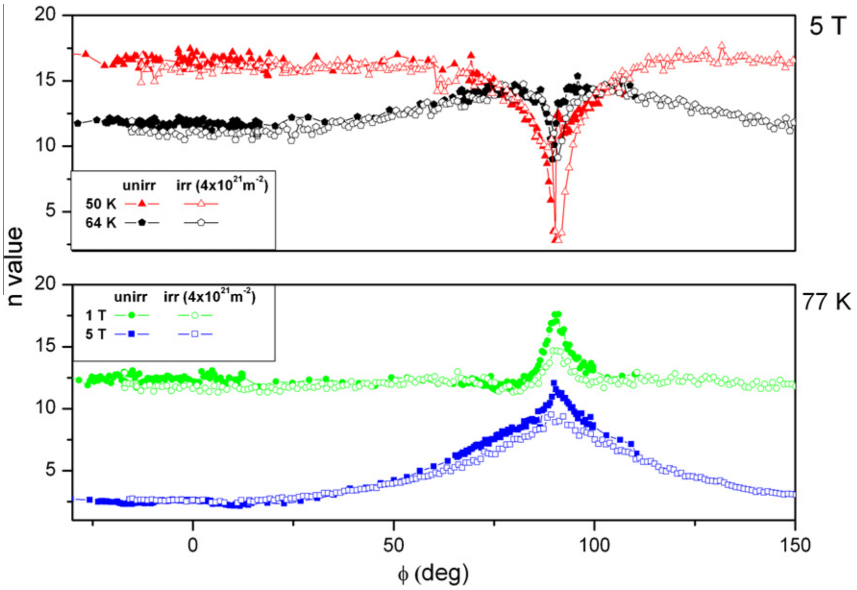

Fig. 4. n-Values obtained from $J_c(\Phi)$ measurements before and after irradiation.

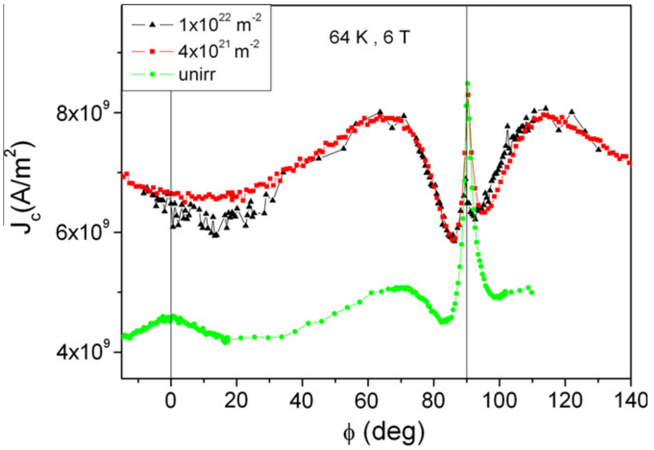

Fig. 5. Comparison of $J_c(\Phi)$ prior to and after irradiation to different fluences at 64 K and 6 T.

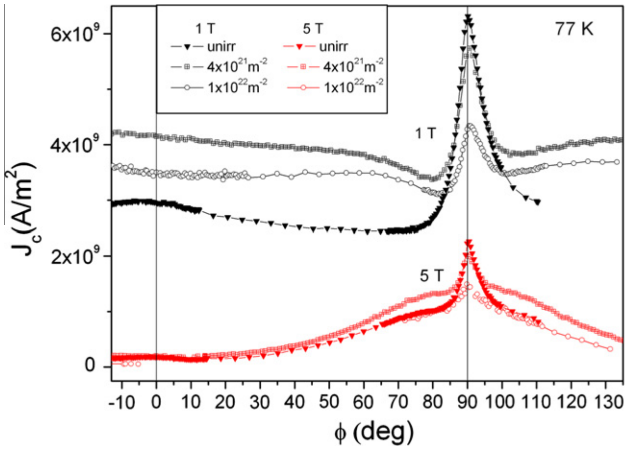

Fig. 6. Comparison of $J_c(\Phi)$ prior to and after irradiation to different fluences at 77 K and 5 T, 1 T.

fields H and high currents, but at 64 K or 50 K, where the currents are relatively high, no shift is observed, whereas it occurs at 77 K, where the currents and the self field are small. Also the same positions of the peak at smaller fields and relatively high currents (e.g. $I \approx 30$ A at 64 K, 3 T) and in high fields and small currents (e.g. $I \approx 0.1$ A at 77 K and 6 T) are in contradiction to this model.

To further investigate the pinning mechanism, the samples are irradiated by fast neutrons. The resulting plots are shown in Figs. 5 and 6. We note an overall improvement of $J_c(\Phi)$ and also a strong reduction of the $J_c(\Phi)$ anisotropy. The most interesting results refer to the position of the *ab* and of the *second peak*. The *ab peak* remains on its position at $\Phi = 90°$ at all fields and temperatures. On the other hand, the *second peak* disappears and is replaced by a local $J_c(\Phi)$ minimum at 64 K. At 77 K the $J_c(\Phi)$ curve is rather flat in this angular range. The $J_c(\Phi)$ asymmetry survives all irradiation steps. The surrounding of the *ab peak* remains asymmetric in all measurements. Because of the introduction of randomly distributed pinning centers by the irradiation, the asymmetry is suppressed in some regions of $J_c(\Phi)$, and features like shoulders close to $H \parallel ab$ (e.g. at 65° and 115° in Fig. 5) are created and seem to be symmetric. Similar shoulders in YBCO tapes were reported [20], but their origin could not be satisfactorily explained yet.

4. Conclusions

State-of-the-art coated conductors from SuperPower were investigated. Angular resolved transport measurements show an asymmetry of the $J_c(\Phi)$ curves similar to that observed in thin films containing tilted *ab* planes with respect to the tape surface. A highly sensitive Hall probe was employed to determine the orientation of the *ab* planes in the CC. The *ab peak* was always at $\Phi = 90°$, i.e. parallel to the sample surface. Beside this asymmetry also a shift of the *second peak* was observed. This shift occurs at 77 K and low fields. The peak occurs at $\Phi = 0°$ at high fields and at all temperatures. We investigated the $J_c(\Phi)$ asymmetry also after irradiation to fast neutron fluences of up to 1×10^{22} m^{-2}. The asymmetry of $J_c(\Phi)$ remained after all irradiation steps, but mainly in the angular range close to the *ab peak*.

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