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Enhancement of the fishtail effect in the $DyBa_2Cu_3O_{7-\delta}$ single crystal at magnetic field tilted from the c-axis

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We studied angular and temperature dependences of the irreversible magnetisation on a twin-free $DyBa_2Cu_3O_{7-\delta}$ single crystal both before and after irradiation with Pb-ions. The irradiation produced columnar tracks along the c-direction which increased significantly the induced current density j_s. The fishtail effect observed before irradiation was shifted to higher temperatures but survived. At high fields (above 2.4 T) the magnetic hysteresis loops became flat, their height being nearly field independent. In the high-field range a distinct difference in the angular dependences of the unirradiated and irradiated sample was observed whereas at low fields the angular behaviour was qualitatively the same for both samples. This fact points to the qualitative difference in the flux pinning processes governing the high-field and central peak regions. The differences imply that the central peak might be mainly due to the in-plane components of the internal field in contrast to the high-field range where the c-axis component of the internal field predominates.

Key words: fishtail effect, $DyBa_2Cu_3O_{7-\delta}$ single crystal, critical currents, relaxation.

1. Introduction

The shape of the magnetic hysteresis loop (MHL) at intermediate and high temperatures where a deformation called the fishtail or peak effect occurs has recently attracted particular interest. Many new papers dealing with magnetic properties of high T_c superconductors give evidence that this effect is neither a specific feature of some particular material nor due to a special sample shape. The experiments rather favour an effect inherent to the vortex system and its interaction with the pinning structure.

There are two categories of approaches to the problem, the static ones [1, 2] which attribute the fishtail effect to some additional pinning at high fields, and the dynamic ones [3, 4] pointing to the enhanced relaxation at low fields around the fishtail minimum. However, the shape of the hysteresis loop is the result of a competition between the *magnetic induction* in changing external fields and the *pinning force* that seek to build up an internal field gradient in the sample and *relaxation effects* which counteract this process [4, 5]. The static and dynamic approach are, therefore, only two sides of the same coin.

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Some recent papers investigated the shape of the MHL at high fields in dependence on the character of the vortex interaction with different types of a pinning structure [4, 6, 7]. In twin-free $REBa_2Cu_3O_7$ single crystals ($RE \equiv$ rare earth) with a random point-like pinning structure this interaction results in a high-field (fishtail) maximum [4, 7, 8]. Its shape can be approximated [8] by the function $j_{sc}(b) = b^m \times \exp[(m/n) \times (1 - b^n)]$ where j_{sc} and b are the critical current density j_s and the applied field B normalized to the coordinates of the fishtail maximum, (j_p, B_p), respectively, m and n are numerical constants used as fitting parameters.

In this paper we investigate angular and scaling properties of the irreversible magnetisation in a twin-free $DyBa_2Cu_3O_7$ single crystal before and after irradiation with Pb-ions. We want to demonstrate a significant difference in the temperature and angular dependence of the low- and high-field part of MHL and to discuss the potential origin of these differences with a particular respect to the fishtail phenomenon.

2. Experimental procedure

Torque hysteresis loops were measured on a twin-free $DyBa_2Cu_3O_7$ single crystal before and after irradiation with Pb-ions. Dimensions of the crystal ($a \times b \times c$) were $0.97 \times 1.23 \times 0.015$ mm^3. The crystal was irradiated at GANIL, Caen, using Pb ions with energy $E = 0.9$ GeV and the fluence $\phi = 1.15 \times 10^{11}$ ions cm^{-2}. The effective dose-equivalence field (the field where the average density of vortices equals the mean density of columnar tracks) was $B_\phi \approx 2.4$ T. The applied magnetic field ranging up to ± 7 T was oriented at an angle Θ with respect to the direction of the columnar tracks (parallel to the c-axis of the sample).

The torque loops measured using a capacitance torque magnetometer were transformed into the MHL by means of the extended Bean model $j_s = \tau/(\Omega B \sin\Theta)$ where τ is the torque and $\Omega = a^2(b - a/3)c/4$ is the geometrical factor. All the MHLs were recorded with the field sweep rate 40 mT s^{-1}. We assumed that the magnetic moment component perpendicular to c-axis is negligible and does not significantly contribute to the torque.

3. Results and discussion

Figure 1 shows the change in the flux pinning caused by the irradiation. For both the unirradiated (U) and the irradiated (I) sample the steep parts of the MHLs on the field reversal line up indicating a good scaling of the torque with the c-axis component of external field. It confirms that the contribution of the component of magnetic moment perpendicular to c-axis, if any, is negligible (see also, e.g. [2]).

At high fields the unirradiated sample exhibits quite a good scaling of the MHLs with $\cos\Theta$: All curves tend to the same envelope (Fig. 1A).

Quite different behaviour is observed at high fields on the sample I: (i) The current density is much higher due to more effective pinning on the columnar tracks. (ii) The MHL becomes flat at high fields forming a plateau instead of a fishtail maximum. It looks like a saturation effect. A similar behaviour was observed in twinned [7] and in Ni-doped YBCO single crystals [9]. The change of the fishtail shape with temperature is documented on Fig. 1(B–F). Except for an exponential decay of j_s with temperature (similar as in the unirradiated samples), the shape of the high-field part of MHL does practically not change in the investigated temperature range (10 K, 50 K). (iii) The critical currents have a pronounced angular dependence at high fields. This feature is due to the specific character of the vortex interaction with the columnar defects [6, 10]. While at low tilt angles each 3D vortex is trapped on the individual columnar track in most of its length, with increasing Θ the vortices are cut into shorter and shorter fractions trapped on the neighbouring columns and connected by kinks. The enhanced pinning on the columnar tracks, especially at the tilt angles $\Theta \leq 25°$, is illustrated by the angular dependences of j_s ($B_c = 3$ T) plotted for different temperatures in Fig. 2A. At the angles above 25° the angular dependence becomes much weaker and can be approximated by a cosine function with an additive positive constant.

At low fields the temperature and angular dependence of the MHL seem to be similar for both samples. The

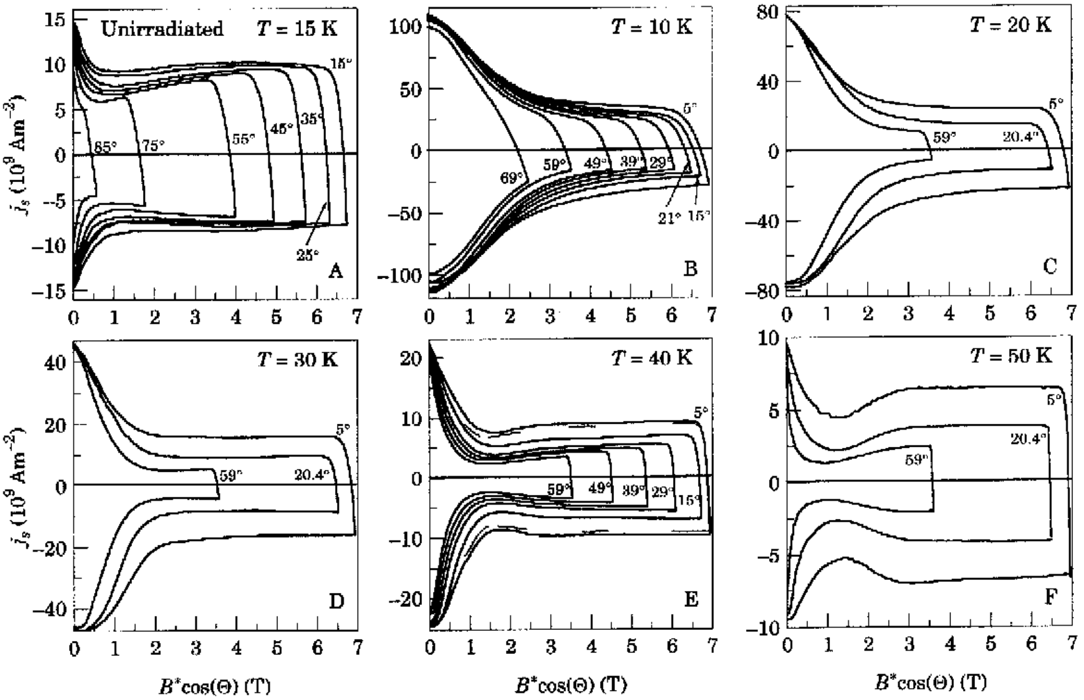

Fig. 1. Angular dependence of the MHL shape for sample U (A) and sample I at different temperatures (B–F).

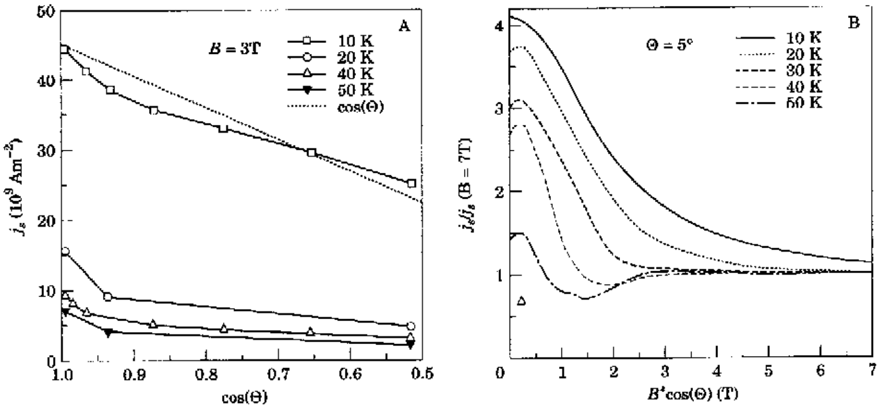

Fig. 2. (A) The angular dependence $j_s(\cos\Theta)$ for $B = 3$ T. The dotted line indicates the pure cosine dependence for $T = 10$ K; (B) The field dependences of the MHL normalized size $j_s/j_s(B = 7\text{ T})$ for different temperatures. For $T = 10$ K the $j_s(B = 7\text{ T})$ was reduced by 10% to take into account that the central peak extended above 7 T.

central peak is about ten times higher and much broader after the irradiation than before but its size rapidly drops with increasing temperature. When the halfwidth of the central peak drops below ≈ 2.4 T (which is approximately equal to B_ϕ), the MHL starts to deform and the fishtail minimum appears. This situation takes place above $T = 30$ K, approximately at the same value of j_s as before the irradiation (compare Fig. 1A and E). It indicates that the shape of the central peak is governed by the geometry and by the magnitude of the average currents flowing in the sample which, in turn, reflect the pinning conditions at the given temperature.

The central peak height and width decrease rapidly with increasing temperature, much more rapidly than the size of the MHL at high fields does. A particular effect on the reduction of the central peak width has the increasing angle Θ. A different temperature scaling of the low- and high-field part of the MHL is illustrated in Fig. 2B where j_s normalized to the value at $B = 7$ T is plotted for $\Theta = 5^\circ$ and different temperatures as a function of the scaled field. Whereas at high fields nearly all curves fall onto the same envelope, the low-field peak develops with temperature in a quite different way.

A simple explanation of the above observations might be that the induced critical currents in the central peak region originate primarily from the in-plane components of the self-fields and the corresponding internal field gradient across the sample thickness, whereas at high fields the shape of the MHL is primarily due to the component of the internal field parallel to c-axis [11]. This idea is also supported by calculations of the remanent moment in samples with a large aspect ratio [12].

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