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Vortex-activation energy and critical currents of $Y_1Ba_2Cu_3O_{7-\delta}$ thin films containing screw dislocations

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Torque-magnetometry was performed on a $Y_1Ba_2Cu_3O_{7-\delta}$ thin film containing screw dislocations. By varying the sweep-rate of the applied magnetic field, the activation energy of the flux-lines $U(j,B,T)$ was investigated. Assuming a linear or logarithmic current dependence for $U(j)$, the pinning energy $U_c(B,T)$ and critical current density j_c could be determined. For both current dependences, $U_c(B,T)$ was found to increase strongly at fields ≤ 0.25 T. This behaviour could be related to flux-pinning caused by screw- and edge dislocations. For fields applied at different angles, the measured magnetization was dependent on the perpendicular component of the applied magnetic field, in agreement with the behaviour expected for a thin film with a thickness d below the penetration depth λ.

1.Introduction

Recently, a high density of screw dislocations ($\approx 10^{13}$ m^{-2}) in concurrence with surface modulations were observed by means of STM in sputtered and laser ablated $Y_1Ba_2Cu_3O_{7-\delta}$ thin films [1][2]. For these thin films, screw- and edge dislocations, point defects as well as a combination of these imperfections have been suggested as possible pinning centres [3].

The mechanisms of pinning by the screw dislocations and surface modulations were discussed in a previous article [4]. Assuming the screw dislocation centre to consist of disordered (non-superconducting) material, the screw dislocation centre will act as a strong attractive pinning centre. At fields below the matching field B_m, where the flux line lattice parameter a_o ($a_o = 1.075(\Phi_o/B)^{1/2}$, with Φ_o the flux quantum) equals the average distance between the screw dislocation centres d_{screw}, the critical current is determined by the pinning force exerted by the screw dislocations only. A background pinning mechanism due to impurities and (oxygen) vacancies was proposed to account for the measured critical currents at fields far above B_m, as the shear interaction of the flux line lattice alone was was estimated too small. The observed temperature dependence of the critical current density, determined by magnetization measurements, at very low and higher magnetic fields was subsequently found to be in reasonable agreement with the expected behavior based on the mechanism outlined above. In the present paper we report on magnetization experiments on $Y_1Ba_2Cu_3O_{7-\delta}$ thin films containing screw dislocations at different sweep rates in order to investigate the field dependence of the activation energy $U(j,B,T)$. Magnetization experiments with the field applied at different angles are also presented.

2. Determination of the activation energy from magnetization experiments.

Commonly the critical current density J_{cm} obtained from magnetization experiments is found by taking directly the width of the irreversible magnetization loop according to the Bean-model. However, relaxation effects of the flux lines due to thermal activation are then neglected. As a result, the $J_{cm}(B)$ dependence obtained in this way is influenced by extrinsic effects like the sweep-rate of the applied field due to the continuous relaxation of the flux lines [5]. Taking into account the relaxation effects, one can obtain information concerning the average activation energy $U(j,B,T)$ by executing magnetization experiments at different sweep-rates. This can be seen in the following way. Performing a magnetization experiment at a certain sweep rate $\partial B_{ext}/\partial t$ is equivalent to the application of an tangential electric field E $\approx (\partial B_{ext}/\partial t)V/S_V$ at the surface of the sample [6]. Here V/S_V is the ratio of the sample volume to the surface area. Due to this electrical field, the vortices will move towards the interior of the sample under the influence of a Lorentz force with a velocity $\mathbf{v}_\phi$, which is given by $\mathbf{E} = \mathbf{B} \times \mathbf{v}_\phi$, with $\mathbf{B}$ the local magnetic induction. The dependence of the vortex velocity v_ϕ on the activation energy $U(j,B,T)$ can be expressed as [6] $v_\phi = (j\rho_f/B)exp(-U(j)/kT)$, with j the current density, ρ_f the flux-flow resistivity given by $\rho_f \approx \rho_n B/B_{c2}$, in which ρ_n is the normal state resistivity and B_{c2} the upper critical field. Writing the electrical field at the sample surface in terms of the sweep-rate of the applied magnetic induction and combining the expressions for E and v_ϕ, one obtains

$$\frac{\dot{B}_{ext}V}{S_V} = \rho_{f,s} j_s exp\left(-\frac{U(j_s)}{kT}\right) \quad (1)$$

where the subscript s denotes evaluation of the quan-

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tities at the surface of the sample. With the above relation between $U(j_s)$ and the experimental parameter j_s, one could try to determine the functional dependence of $U(j,B,T)$ without using an explicit expression for the current dependent part of U. This has proved to be rather difficult. Therefore we proceeded using two models for $U(j)$, namely the Kim-Anderson model $U(j) = U_c(1-j/j_c)$, and the logarithmic model $U(j) = U_c ln(j_c/j)$, which was experimentally found from I-V characteristics in $Y_1Ba_2Cu_3O_{7-\delta}$ thin films [7]. Here j_c and $U_c(B,T)$ are the critical current density and the pinning energy, respectively. Substituting the Kim-Anderson relation into Eq. (1) we obtain

$$j_s = j_c\left(1 + (kT/U_c) ln\left(\frac{\dot{B}_{ext}V}{S_V\rho_{f,s}j_s}\right)\right) \tag{2}$$

By plotting j_s as a function of $ln(\dot{B}_{ext}/j_s)$ one expects a straight line with a slope $s = j_c kT/U_c$ and an intercept $c = j_c + (j_c kT/U_c) ln(V/(S_V\rho_f))$.

With the logarithmic model one gets

$$j_s = \left(\frac{\dot{B}_{ext}V}{S_v\rho_f}\right)^{\frac{kT}{kT+U_c}} j_c^{\frac{U_c}{U_c+kT}} \tag{3}$$

From Eq. (3), $ln(j_s)$ plotted as a function of $ln(\dot{B})$ should give a straight line with a slope $s = kT/(kT + U_c)$ and an intercept $c = (U_c/(U_c + kT)) ln(j_c) + (kT/(U_c + kT)) ln(V/(S_V\rho_f))$. The relations derived above between j_s or $ln(j_s)$ and $ln(\dot{B}_{ext})$ are the starting point for the evaluation of the experimental data in Section 4.

3. Experimental

The $Y_1Ba_2Cu_3O_{7-\delta}$ thin film was made by DC hollow cathode magnetron sputtering on an (100) oriented $SrTiO_3$ substrate. Details on the preparation procedure have been given elsewhere [8]. The thickness of the film d was ≈ 130 nm and the screw dislocation density was found to be $(12.3\pm0.8)\times10^{12}$ m^{-2} giving a mean distance between the screw dislocations d_{sd}=285 nm and a matching field B_m=0.03 T. On a separate section of the film, the critical temperature was determined resistively giving $T_c(R = 0)$=86.5 K.

Magnetization measurements were performed on a more or less circular shaped part of the sample, with a radius between 0.5 and 0.6 mm using a torque-magnetometer, which could be rotated in the external field of a superconducting magnet with an absolute accuracy of ≈ 0.3 degrees. The sweep-rate of the applied magnetic field was varied between 0.3 mT/s and 36 mT/s. Eddy currents in the BeCu sample-mounting plate were found to give an additional contribution to the measured magnetic moment, especially at the higher sweep-rates. A correction was made for this contribution, based on measurements at 55.8 K [9].

The magnetic moment m has been determined from the torque τ by $m = \tau/(\mu_o H_{ext} cos\theta)$, where θ is the angle between the field and the film surface and m is assumed to be perpendicular to the surface of the film which is reasonable for a film with a thickness below the penetration depth. For a further evaluation, the measured magnetic moment has to be expressed in terms of a surface current density j_s. When the magnetic flux lines have fully penetrated the sample, m is directly proportional to j_s, if we assume a homogeneous current distribution in the interior of the sample. For simplicity, we have taken this assumption to be equally valid for the increasing and decreasing part of the magnetization loop, which is reasonable in most cases [5][10]. The width of the magnetic moment loop Δm is then related to j_s by Bean's formula for a cylinder of radius R and height h i.e. $j_s = 3\Delta m/(2\pi R^3 h)$.

4. Results and discussion

Results of magnetization measurements at T=8.9 K and a fixed sweep-rate of 6 mT/s are shown for different values of θ between 45° and 85° in Fig. 1, where we have plotted Δm as a function of $H_z \equiv H sin\theta$.

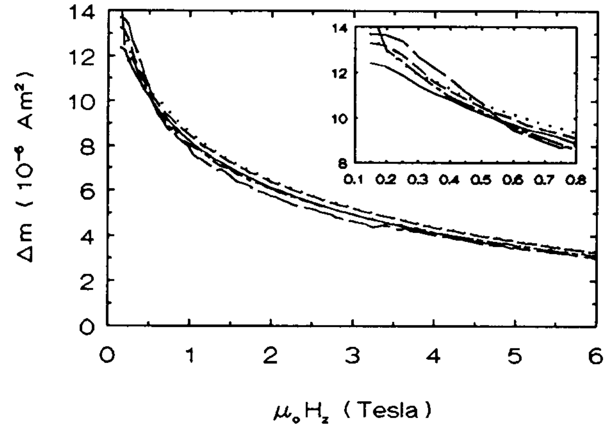

Fig. 1. Δm versus the perpendicular component H_z at T= 8.6 K, for different angles of the applied field. —:θ=45°; · · ·:θ=61.2°; – – –:θ=71.3°; — – —:θ=81°; — —:θ=85°. Inset: Blow-up of the low field section of the data.

To eliminate a possible source of systematic error, we have included in H_z the perpendicular component of the demagnetization field generated by the sample, determined according to the method from Däumling and Larbalestier[11]. For Δm this proved to be a minor correction.

By plotting the data this way, the measured values of Δm show approximate scaling behaviour. This scaling means that the pinning behaviour is mainly determined by the perpendicular component of the magnetic induction, as expected for a film with a thickness smaller than the penetration depth. At low fields, the curves show more dispersion (see inset of Fig. 1), though a systematic increase of Δm for angles increasing towards $\theta = 90^\circ$ could not be established.

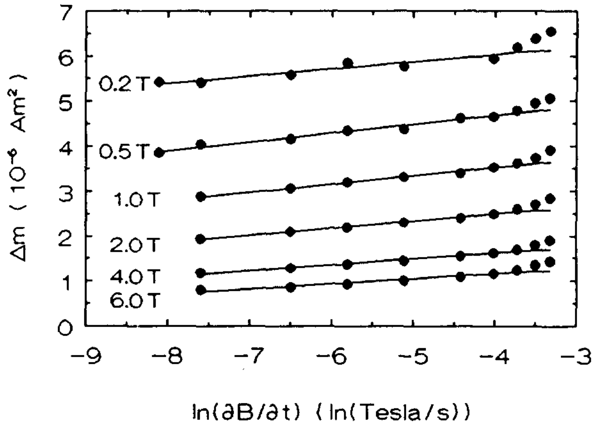

Fig. 2. Δm versus $\ln(\dot{B}_{ext})$ at T=30.8 K and $\theta = 61.2^\circ$ for fields of 0.2 T, 0.5 T, 1.0 T, 2.0 T, 4.0 T and 6.0 T. The drawn lines are fits according to Eq. 2.

Next, the dependence of the width of the magnetic moment loop on the sweep-rate of the applied field is discussed. In Fig. 2, we have plotted measured values of Δm against $ln(\dot{B}_{ext})$ rather than $ln(\dot{B}_{ext}/j_s)$ for reasons of clarity, for fields ranging between 0.2 T and 6.0 T, at 30.8 K. The angle θ was fixed at 61.2 degrees for all measurements. The lines in Fig. 2 are fits according to Eq. (2), using the Kim-Anderson current dependence of the activation energy. The deviation between the data points and fits is probably due to a remaining eddy current contribution, despite the corrections made. Fits of a comparable quality could be obtained using the logarithmic dependence of the activation energy $U(j, B, T)$, using Eq. (3) (not shown).

From these fits we have obtained the prefactor of the activation energy U_c and j_c via the corresponding expressions for the slope s and the intercept c given in Sec. 2. For the Kim-Anderson model, the values of U_c and j_c can only be obtained by inserting additional experimental values, V/S_V, ρ_f and B_{c2}, making the results somewhat dependent on the precision of these data. For the logarithmic current dependence, U_c follows directly from the slope, but the value of j_c can only be obtained with logarithmic precision, making the outcome very sensitive to experimental errors.

Results for U_c are given in Fig. 3, where U_c/KT is given as a function of the perpendicular component of the applied field at T=21.8 K and T=30.8 K, using both the linear and the logarithmic current dependences. All curves show a large increase of U_c for H_z ≤ 0.25 T, which we think is caused by an increased contribution to the pinning energy arising from screw dislocations.

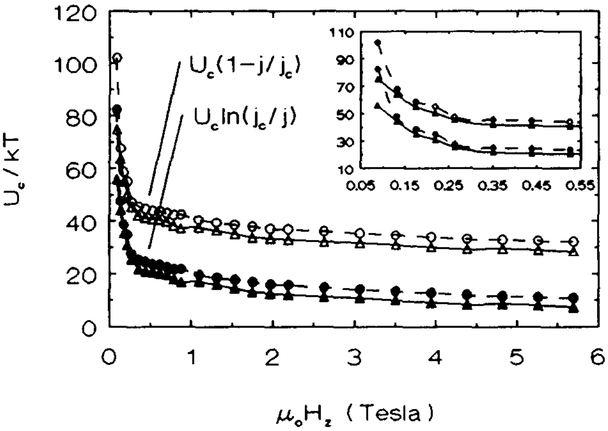

Fig. 3. The dependence of U_c/kT on H_z for a linear (upper data set; open symbols) and logarithmic (lower data set; closed symbols) current dependence of $U(j)$ at T=21.8 K (o,•) and T=30.8 K (△,▲). Inset: Blow-up of the low field data section.

From the logarithmic model, the values of U_c vary between 1540 K ($\mu_o H_z$=0.1 T) and 240 K ($\mu_o H_z$=5.25 T) at 30.8 K. For the Kim-Anderson model, the corresponding values are 2130 K and 890 K, respectively. From Ref. 3, the activation energies at T=30 K estimated for pinning by screw-dislocations and oxygen vacancies are 1.3 x 10^4 K and 60 K, repectively. Here we have assumed the screw dislocation core to extend along the total film thickness and one oxygen vacancy per 80 oxygen atoms per CuO_2 layer [3]. In comparison, the values of U_c obtained from the logarithmic model are in a somewhat better agreement with the estimated ones. However, the absolute values of U_c at T=21.8 K and T=30.8 K are approximately equal for the logarithmic model and for the Kim-Anderson model, U_c at T=30.8 K is even slightly higher. This could be due to an insufficient correction for the eddy current contributions at lower temperatures. Analysis of the data using the collective creep/vortex glass model, $U = U_c((j_c/j)^\mu - 1)$ [12], is currently in progress.

Results for j_c are given in Fig. 4, where normalized values of j_c obtained from the Kim-Anderson model current dependence are given as a function of the perpendicular component of the applied magnetic field, for T=21.8 K and T=30.8 K. Normalized values of Δm are also given in Fig. 4. Values of j_c obtained from the logarithmic current dependence (not shown) showed much scatter so a systematic dependence on the applied magnetic field could not be obtained.

As can be seen, the field dependence of Δm is larger than j_c, in agreement with predictions by Schnack et al.[5]. The absolute values of j_c vary between 2.0×10^{11} A/m^2 (0.1 T) and 8.4×10^{10} A/m^2 (5.25 T) at T=30.8 K. Corresponding values of J_{cm} determined using Δm are 1.4×10^{11} A/m^2 and 2.3×10^{10} A/m^2, respectively. These values are in a reasonable agreement with estimated values for j_c at T=30 K due to pinning by screw dislocations and oxygen vacancies, 3.7×10^{11} A/m^2 and 1.6×10^{11} A/m^2 , respectively [4].

However, at fields $\leq$ 0.25 T j_c seems to saturate, in contrast to the measured values of J_{cm}. This saturation was observed by other authors from transport measurements [13] and could also be an indication of an increased contribution to the flux-pinning by screw-dislocations, as the critical current due to these defects is expected to be field independent [4].

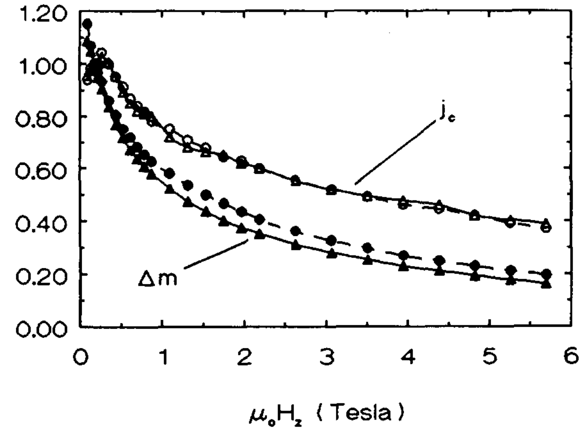

Fig. 4. $j_c(\mu_oH_z)/j_c(0.175T)$ as a function of H_z, obtained using the Kim-Anderson model for $U(j)$ (open symbols). Normalized values of Δm are given by closed symbols. T=21.8 K (o, •); T=30.8 K (△, ▲).

The value of 0.25 T mentioned above is much higher than the matching field determined by the screw dislocations density (B_m=0.03 T). However, the actual value of B_m can be much higher due to edge-dislocations located at the grain boundary in between neighbouring screw dislocations (see contribution of V.Pan, this meeting).

5. Conclusions

For magnetic fields applied at different angles, the value of Δm was found to be determined by $Hsin\theta$, as expected for a thin film. At low fields no significant increase of Δm was seen for fields applied increasingly towards the perpendicular direction.

By performing magnetization experiments at different sweep-rates, we have obtained values of U_c and j_c, using both a linear and a logarithmic current dependence of the activation energy $U(j)$. For both cases, the value of $U_c(B,T)$ was found to increase strongly at fields $\leq$ 0.25 T. This can be attributed to an increasing contribution from strongly pinning screw- and edge dislocations to U. Also, the observed leveling-off of j_c, obtained using the Kim-Anderson model, at fields $\leq$ 0.25 T can be ascribed to the same mechanism.

The difference between the value of 0.25 T and B_m, calculated from the screw dislocation density, can be due to the occurrence of strong pinning edge-dislocations at the boundary between the screw-dislocations, giving rise to a significant increase of the actual value of B_m.

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References.

[1]. M.Hawley, I.D.Raistrick, J.G.Beery,R.J.Houlton, Science **251** (1991) 1587.

[2]. C.Gerber, D.Anselmetti, J.G.Bednorz, J.Mannhart, D.G.Schlom,Nature **350** (1991) 277.

[3]. see e.g. P.H.Kes in *Phenomenology and Applications of High Temperature Superconductors*, ed. K.Bedell et. al. (Addison-Wesley, New York, 1992), p. 390.

[4]. H.Douwes, P.H.Kes, Ch.Gerber, J.Mannhart, to appear in the Proc. of the Conf. on Critical Currents in High-T_c Superconductors, Vienna, Austria, April 22-24 1992, Cryogenics 32 (1992).

[5]. H.G.Schnack, R.Griessen, J.G.Lensink, C.J. van der Beek, P.H.Kes, Physica C **197** (1992) 337.

[6]. C.J. van der Beek, Flux pinning and creep in extremely anisotropic type-II superconductors, Ph.D. thesis Leiden University, 1992.

[7]. E.Zeldov, N.M.Amer, G.Koren, M.W.McElfresh, A.Gupta, R.J.Gambino, Appl. Phys. Lett. **42** (1990) 2639.

[8]. D.G.Schlom, D.Anselmetti, J.G.Bednorz, R.F.Broom, A.Catana, T.Frey, Ch.Gerber, H.-J.Güntherodt, H.P.Lang, and J.Mannhart, Z. Phys. B **86** (1992) 163.

[9]. H.H.Wen, private communication.

[10]. C.J. van der Beek, G.J.Nieuwenhuys, P.H.Kes, H.G.Schnack, and R.Griessen, Physica C **197** (1992) 320.

[11]. M. Däumling and D.C.Larbalestier, Phys. Rev. **40** (1989) 9350.

[12]. M.V. Feigel'man, V.B. Geshkenbein, A.I.Larkin and V.M. Vinokur, Phys. Rev. Lett. **63** (1989) 2303.

[13]. J.Mannhart, D.Anselmetti, J.G.Bednorz, A.Catana, Ch.Gerber, K.A.Muller and D.G.Schlom, Z.Phys. B **86** (1992) 177.