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FLUX PINNING IN HIGH TEMPERATURE SUPERCONDUCTORS INVESTIGATED BY MAGNETIC RELAXATION MEASUREMENTS[1]

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Different methods for the analyses of measurements of the time dependence of the magnetic moment in high T_c superconductors are discussed. Examples are given for Bi2223-tapes, powder-melt-processed (PMP) YBCO with different oxygen content and melt-textured YBCO with an enhanced fishtail effect. Bi2223 tapes show 2D flux creep behaviour. Whereas in fully oxygenated YBCO 3D behaviour is obtained, a tendency towards 2D is found if the oxygen content is reduced or a pronounced fishtail is present.

In the Shubnikov phase of a superconductor flux lines arrange themselves in a way, such that the Lorentz force, which drives the flux lines into the material is on every point in equilibrium with the pinning force. This equilibrium defines the critical state [1]. As Anderson [2] pointed out, a possibility exists for flux movement away from this critical state, because of thermal activation at nonzero temperatures. According to Andersons theory of flux creep 'flux bundles' jump over pinning barriers with a rate according to an Arrhenius law $\nu = \nu_0 \exp(-U/kT)$, where ν_0 is an attempt frequency and U the effective activation energy, which increases monotonically with time, leading to a logarithmic time dependence of $M(t)$. In its simplest form [3] U is given by $U = U_0 - |F|VX$ where F is the driving force, V the flux bundle volume and X the hopping distance or pinning length. For $U \gg kT$ the deviation of the system from the critical state is small. Then $|F|$ is equal to the elementary pinning force $F_p = J_cB$ and the effective pinning barrier is given by $U_0 = J_cBVX$. Whereas from measurements of the critical current density J_c only the relation U_0/VX can be deduced, the measurements of the time decay of the magnetic moment allows in principle to determine U_0 and VX independently.

By the flux diffusion equation [4] $\partial B/\partial t = \nabla[BX\nu_0 \exp(-U/kT)]$ (B is the local field), the logarithmic time dependence of the magnetic moment follows under the assumption $U \gg kT$. This condition is fulfilled for classical superconductors, but in high temperature superconductors U is normally much lower, because the coherence length ξ is much smaller and kT is very large for temperatures near T_c. Nevertheless numerical calculations of the flux diffusion equation [5] show that 90% of the relaxations in high T_c superconductors are expected to be also logarithmic. The simplification, when

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assuming only one barrier height can be overcome by taking into account a distribution of activation energies [6]. Also the ansatz of a linear $U(J)$-relation is very crude, because it implies a V-notch like shaped pinning potential. For physically more realistic potential shapes, nonlinear $U(J)$-relations are always the consequence. It was shown [6], that for a wide variety of different shapes $U \sim U_p(1-J/J_{max})^n$ with $3/2 < n < 2$ is a good approximation. J_{max} is the maximum current density which pinning potential can sustain in the absence of thermal activation. U_p is the true pinning well height. The Anderson-Kim relation is described by the tangent on the real $U(J)$-curve at that current density, which corresponds to the momentary measuring conditions. Therefore large differences between the linearly extrapolated U_0-value and the real pinning potential barrier height U_p may appear.

As pointed out by Maley et al [8], the shape of the $U(J)$-relation can be determined by plotting $-T\ln|dM(t)/dt| + CT$ against M_{irr}, which is related to J_c via Beans formula [1]. The parameter C follows from $C = \ln(H_a\nu_0 X/2\pi d)$, where d is the thickness of the sample. The appropriate C value, which is assumed to be temperature independent, follows from the condition, that all points have to lie on a smooth curve. The results do not depend very much on C, because it is only a logarithmic correction term. The smoothness can be reached only in the low temperature region, because at higher temperatures a change in the pinning well height U has to be taken into account. Tinkham [9] has proposed, that the temperature dependence of the pinning well height should be governed by the temperature dependence of those parameters, which are fundamentally related to pinning. A Ginzburg-Landau treatment leads to $g(T) \sim (1-t^2)$ with $t = T/T_c$. Sometimes better results have been obtained by using $t = T/T_{irr}$ [10], where T_{irr} is the irreversibility temperature. A third possibility is to use a value for C, obtained only from the fit to the low temperature regime ($T < 15$ K). $g(T)$ is then determined from the constants, which are necessary to bring the relaxation curves for all other temperatures on a smooth curve.

A logarithmic $U(J)$-dependence was proposed from the analysis of resistivity measurements for a variety of different samples [11]. A more general equation was suggested by Feigel'man et al [12] on the basis of the collective pinning theory, where the pinning on randomly distributed weak pinning centres is discussed by taking into account the elasticity of the flux line lattice. Because of the small coherence length (ξ), tiny defects (e.g. oxygen vacancies, dislocations) are effective pinning centres. This theory predicts for $J \ll J_c$ an inverse power law $U = U_i(J/J_c)^{-\mu}$, where U_i is the activation energy for $J = J_c$ and the exponent μ is dependent on the dimensionality and the particular flux creep regime. An interpolation formula for the whole J region is given by $U = U_i[(J_c/J)^{\mu} - 1]$, where for $\mu = -1$ the Anderson and for $\mu = 0$ the Zeldov equation is obtained. In the case of 3D pinning $\mu = 1/7, 3/2$ and $7/9$ is expected [12] for pinning of single vortices, small flux bundles (sfb) and large flux bundles (lfb), respectively. If ξ is smaller than the distance of the superconducting layers, flux decouples into so called pancakes and 2D flux creep takes place. In that case $\mu = 9/8$ (svc) and $1/2$ is proposed [13,14] for single vortex (svc) and collective vortex creep (cvc).

There are two possibilities to analyse the $U(J)$-curves in terms of the collective pinning theory: i) to fit them by the interpolation formula ii) to do it graphically by

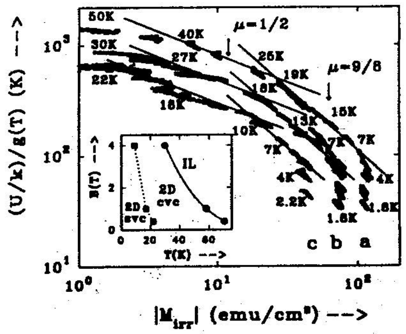

Fig.1 $U(J)$-relation for a Bi2223-tape measured at 1 T (a), 3 T (b) and 5 T (c), (C = 15, $g(T) = 1-(T/T_c)^2$, T_c = 106 K, IL irreversibility line).

plotting $\ln(U)$ vs $\ln(|M_{irr}|)$. In the first case the full J region can be covered, but in the fit μ is constrained to be independent of temperature. Therefore a fit may lead to wrong μ values, when μ depends on the current density. This can be checked, if the fit is performed for different temperature intervals. In the graphic representation $\ln(U)$ vs $\ln(|M_{irr}|)$ μ appears as the slope on the curve, according to the invers power law. This method has the disadvantage, that it is only applicable for current densities $J \ll J_c$. One can assume that this condition is fulfilled in most of the temperature range, because due to the small sweep rate used for the measuring field the critical state is never reached. The best proof for this assumption is fitting the low temperature regime by the interpolation formula and comparing the obtained exponent μ with the slope obtained from the graphic analysis. If they are equal, the condition $J \ll J_c$ should be fulfilled.

In the following, examples for such analysis of the measurements of the time dependence of the magnetic moment performed in a VSM on three different textured high T_c superconductors are given. In Fig.1 the $U(J)$-curves for a Bi2223-tape are shown in a double logarithmic representation for three different fields applied perpendicular to the tape surface. For Bi-superconductors a 2D behaviour is expected, because of the large distance between the CuO_2 sheets, which is larger then the coherence length in c-direction. In that case theory predicts $\mu = 9/8$ if the pancakes are moving independently, and $\mu = 1/2$ if they creep collectively. The border between the two regimes is reached, if the transverse coherence length $R_c \sim (c_{66}\xi_{ab}/J_cB)^{1/2}$ (with the shear modulus $c_{66} = (B_c^2/4\mu_0)b(1-b^2)$, $b = B/B_{c2}$ and ξ_{ab} the coherence length in ab-direction) becomes larger than the vortex lattice spacing $a_0 \sim (\phi_0/B_a)^{1/2}$. For single vortex creep the activation volume V should be smaller than or equal to the one of a single pancake $V_{pc} \sim a_0^2 s$ (s is the distance between the CuO_2 planes). V can be obtained from an analysis in terms of activation energy distributions where the relaxation time τ is related to V by $\tau = 2\mu_0 kT/(2\pi\nu_0 V B_a^2)$. Both regimes are observed in the measurements (Fig.1). The extreme large μ-value at low temperatures may either be caused by the fact that the condition $J \ll J_c$ is not fulfilled, or by the influence of quantum tunneling effects. The change from single vortex creep to collective vortex creep is shifted

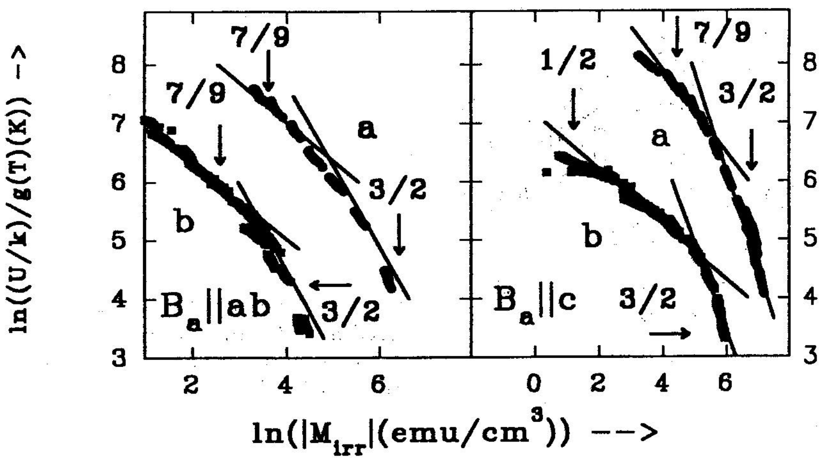

Fig.2 $U(J)$-relation for powder-melt-processed (PMP) YBCO samples with T_c = 92 K (a) and 62 K (b) measured at 3 T; C = 15, $g(T) = 1 - (T/T_c)^2$.

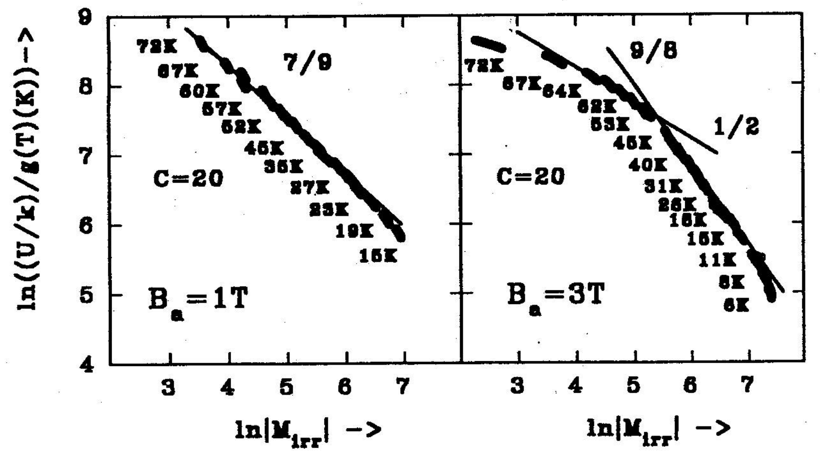

Fig.3 $U(J)$-relation for melt-textured YBCO, determined for $B_a \| c$ with $g(T) = 1 - (T/T_c)^2$, T_c = 88 K.

to lower temperatures for higher fields (Inset Fig.1). This is expected from the above given equations. R_c increases with field, because of the decrease of J_c with increasing B_a.

As a second example we discuss results obtained from measurements of textured powder-melt-processed (PMP) YBCO samples. As seen in Fig.2 for a sample with T_c = 92 K 3D behaviour is obtained, as expected for YBCO, because of the larger coherence length compared to the Bi-samples. The system changes from small flux bundle creep ($\mu = 3/2$) to large flux bundle creep ($\mu = 7/9$) with increasing temperature. But when the oxygen content is reduced, pinning changes from 3D to 2D behaviour. This is shown in Fig.2 for a sample with T_c = 62 K. For $B_a \| (a, b)$ μ is the same as for the 92 K sample (only J_c is reduced), but for $B_a \| c$ μ changes from 3/2 (sfb pinning in 3D) at low temperatures to collective pinning in 2D at lower current densities (Fig.2). Therefore a tendency towards 2D behaviour with decreasing oxygen content is found for these YBCO samples.

In Fig.3 the results for a melt-textured YBCO sample with T_c = 88 K are shown. The sample exhibits a pronounced fishtail effect, which is strongly influenced by the oxygen treatment. From flux creep measurements it is found, that at the field, where the fishtail starts to develop, pinning behaviour changes drastically. Below this field the sample behaves in the usual way: 3D pinning of large flux bundles ($\mu = 7/9$) is obtained in the temperature range 30 to 70 K (Fig.3a). At higher fields, where flux creep is dominated by the pinning centres which are responsible for the fishtail, a change from single vortex creep to collective vortex creep in 2D with temperature appears. Therefore it can be concluded, that in this sample two different types of pinning centres exists. The ones which can be detected in the field regime where no fishtail appears behave in the usual 3D way, and the others, responsible for the fishtail effect, lead to a 2D behaviour of flux creep.

In conclusion, the investigation of the time dependence of the magnetic moment is an important method to get detailed information about the mechanisms of flux pinning in high temperature superconductors. For the analysis several methods of different grade of complexity exist, which all have various restrictions. But a combination of the different analyses lead to physically reasonable results.

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