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Characterisation of the magnetisation hysteresis in RE-123 superconductors by exponentially decaying and power-law functions.

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ABSTRACT: The fully developed fishtail shape of the magnetization hysteresis loops (MHL) in untwined RE-123 bulk materials is well characterized by the logarithmic pinning potential $U(j)$ in frames of the thermally activated pinning process. This type of pinning potential results in a slightly modified exponential decay of critical current density and pinning force density at high fields, fitting well the fishtail shape. The role of the functional parameters is discussed and a comparison is provided with conventional power-law functions. The fit by both types of the model functions is illustrated on the experimental data of a Nd-123 single crystal.

1. INTRODUCTION

The fishtail effect (FE) occurring in the whole family of type-II superconductors promises a particularly interesting use in a variety of levitation applications. In this context the high temperature (RE)$Ba_2Cu_3O_{7-\delta}$ materials (RE-123, RE = rare earth) have attracted a particular interest. The origin of FE in these compounds was identified with pinning on a random pinning disorder and oxygen deficient clusters were found to be the operative pinning defects (Zhukov et al 1995, Däumling et al 1996, Erb et al 1996, Küpfer et al 1998, Nishizaki et al 1998, Nishizaki et al 1999). Though the relevant pinning agent is known, the actual pinning mechanism has not yet been established. The studies of the vortex lattice phase in clean single crystals with a varying oxygen deficiency show that the vortex matter has a rather complex behavior, especially at high temperatures. The FE shape and position dramatically develop with varying concentration of oxygen vacancies. Similar conclusions can be drawn from the studies of additional sources of pinning due to a distribution of normal particles in a superconducting matrix (Muralidhar et al 1998, 1999). Evidently, FE is a complex phenomenon, incorporating interaction of vortex lattice with the operative pinning structure, mutual interactions of vortices, transitions between different vortex matter phases etc. It is therefore rather surprising how well is the FE shape adjusted in the samples with a high concentration of point-like defects (we will denote this state as a saturated FE).

It has been recently shown (Jirsa et al 1997, Jirsa and Pust 1997) that the saturated FE shape is well described by modified exponential functions resulting from the use of the logarithmic potential $U(j)$ in description of magnetic hysteresis in RE-123 materials in terms of thermally activated creep. In this paper we analyze properties of these analytical functions in detail and compare them with the classical power-law ones.

2. LOGARITHMIC POTENTIAL

We consider the thermally activated creep process (Perkins et al 1995, Perkins et al 1996, Jirsa et al 1997, Jirsa and Pust 1997) described by the classical formula

$$E = B\nu\, x\exp\left[\frac{U_{eff}(J,B,T)}{kT}\right] \quad , \qquad (1)$$

where E is the electric field induced in the sample by applied field sweep, ν is the attempt frequency, x is the mean vortex hop distance, and U_{eff} is the effective barrier for thermally activated jumps. This energy barrier is supposed to be a function of temperature, field, and critical current density,

$$U_{eff}(J,B,T) = U_0(B,T)\, V[(J/J_0(B,T)] \qquad (2)$$

where U_0 and J_0 are characteristic energy and current scales. The analysis of experimental data in Tm-123 (Perkins et al 1995) showed that the function $V(J/J_0)$ is logarithmic. This is consistent with the results of transport measurements on different RE-123 samples where an equivalent relation, $J/J_0 = (E/E_0)^{\beta}$, is frequently found, and also with the magnetic data on other RE-123 materials.

Due to the characteristic temperature dependence of FE and the dependence on the actual sample morphology, it is useful to treat the FE data in a reduced form. Then, the FE peak shape either does not change with temperature at all (scales) or varies only slightly. With the logarithmic potential $V(J/J_0)$ we get from equation (1) the field dependence of critical current density in the form $J \propto B^m \exp(cB^{-n})$ and applying conditions for an extreme we arrive in the normalised form

$$j_n = b_p{}^m \exp[(1-b_p{}^n)\, m/n] \qquad (3)$$

where $j_n = J/J_p$ and $b_p = B/B_p$ are the critical current density and applied field, respectively, normalised to FE co-ordinates. The pinning force density $F=BJ$ reads in the normalised form

$$F_n = b_f{}^{m+1} \exp[(1-b_f{}^n)\,(m+1)/n] \qquad (4)$$

where $b_f = B/B_{fp}$ and $F_n = F/F_p$ are the applied field and the pinning force density, respectively, reduced to the co-ordinates of the FE maximum on the $F(B)$ curve, B_{fp} and F_p.

Eqs. (3) and (4) do not reach zero at the irreversibility field. In accord with experiment, the irreversibility field is here defined by means of a precision criterion. For the aim of comparability with the conventional formulas shown below, we express eq. (4) also in terms of the applied field reduced to the irreversibility field, $b = B/B_{\mathrm{irr}}$

$$F_n = (b/b_{pirr})^{m+1} \exp[(1-(b/b_{pirr})^n)\,(m+1)/n] \qquad (5)$$

with $b_{\mathrm{pirr}} = B_{\mathrm{fp}}/B_{\mathrm{irr}}$.

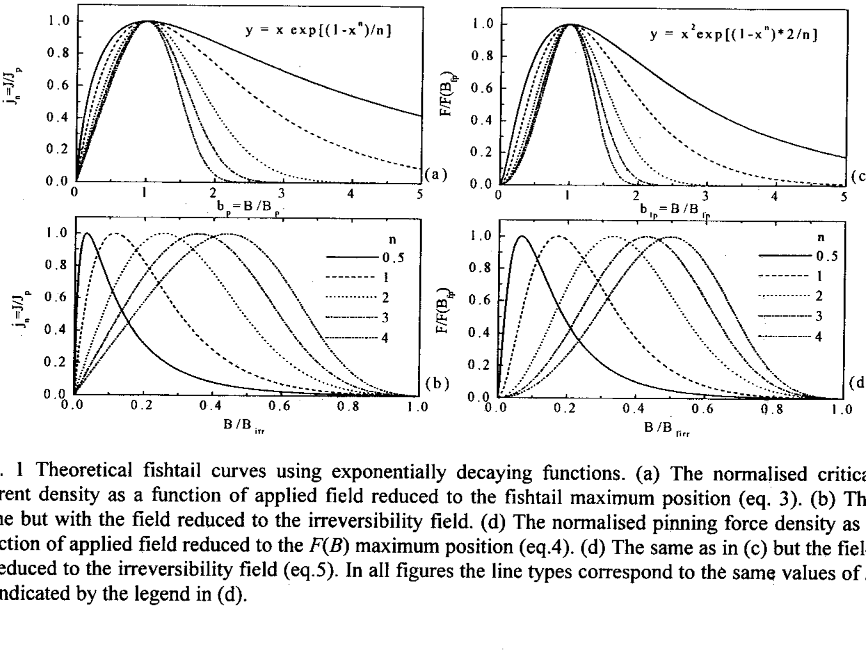

Fig. 1 Theoretical fishtail curves using exponentially decaying functions. (a) The normalised critical current density as a function of applied field reduced to the fishtail maximum position (eq. 3). (b) The same but with the field reduced to the irreversibility field. (d) The normalised pinning force density as a function of applied field reduced to the $F(B)$ maximum position (eq.4). (d) The same as in (c) but the field is reduced to the irreversibility field (eq.5). In all figures the line types correspond to the same values of n as indicated by the legend in (d).

We note that in equations (3) to (5) m can be fixed at 1 (Jirsa and Pust 1997). Then, the entire FE shape is mainly governed by the parameter n, which has been empirically found to range between 0.5 and 4 (Jirsa and Pust 1997). In Fig. 1(a) we present $j_n(b_p)$ curves according to eq. (3) for $m=1$ and n covering all the range of experimentally observed values, from 0.5 to 4. We see that with increasing value of n the fishtail curve becomes narrower. n can therefore serve as a measure of the curve width. As the position of the FE maximum is fixed at 1 in this representation but the curve extends up to irreversibility field, B_{irr}, it is evident that n also reflects the ratio B_p/B_{irr}. This fact is even better seen in Fig. 1 (b) where the applied field is normalised to B_{irr} instead of B_p so that the FE maximum shifts in dependence of the actual n value. Therefore, the additional parameter B_p/B_{irr} in eq. (5) is not independent of n. In Figs 1 (c) and (d) the analogous curves for the normalised pinning force density are shown.

3. POWER-LAW MODEL

The pinning force density in conventional superconductors was empirically found to fit the formula (Fietz and Webb 1969)

$$F \propto B_{c2}{}^r b^p (1-b)^q \tag{6}$$

where $b=B/B_{c2}$ and r, p, and q are positive parameters. This formula is also frequently used for the analysis of FE in high temperature materials. In such a case, B_{c2} is usually replaced by B_{irr}.

For the aim of comparison of the two approaches, we express eq. (6) in the reduced form

$$F_n = \frac{(p+q)^{p+q}}{p^p q^q} b^p (1-b)^q \tag{7}$$

where $F_n=F/F_p$. Though the power-law functions are usually used in the form (6) or (7), it is also possible to derive from eq. (6) the alternative expression for critical current density,

$$j_n = b_p{}^{p-1}[1+\frac{(p-1)}{q}(1-b_p)]^q \,. \tag{8}$$

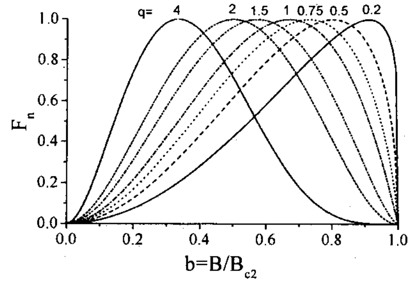

Fig. 2 The theoretical curves modelling fishtail $F_n(b)$ dependence by eq. (7) with $p = 2$ and $q = 0.2$ to 4.

Here $b_p=B/B_p$ is the applied field normalised to FE peak position, B_p.

By comparing eqs. (5) and (6) or (7) we can identify the power p with $m+1$. For $p \leq 1$ the $j_n(b_p)$ curve continuously decays with field and does not produce a maximum. This means that most of the microscopic pinning mechanisms treated so far in terms of power-law potential is irrelevant to the saturated FE in RE-123 materials. The only exception is the vortex pinning by superconducting point- and surface defects, so called $\Delta\kappa$ pinning (Dew-Hughes 1974), with $p=1.5$ and $p=2$, respectively.

The theoretical curves of the normalised pinning force density according eq. (7) with $p=2$ (in accordance with $m=1$) are shown in Fig. 2 for q values between 0.2 and 4. Only the curves with $q >$ 1.5 resemble the saturated FE shape in high T_c materials.

4. APPLICATION TO EXPERIMENT

For illustration we analyse in Fig. 3 the fishtail effect observed on a Nd-123 single crystal. The magnetic hysteresis loops were measured at temperatures 70 K to 88 K by means of a SQUID magnetometer. In Fig. 3 (a) the normalised pinning force density is fitted by means of eq. (5) and (6), in Fig. 3 (b) the corresponding normalised critical currents are presented as a function of the applied field reduced to the FE peak position. Though the exponential functions give nearly perfect fits, the fits by the power-law functions are also good. Both types of fitting functions enable a good fit especially in the case of pinning force density where the stray field effects at low fields are masked. The fitting values of p and q lie high above the theoretically predicted values (for review see e.g. Dew-Hughes 1974 or Fabricatore et al 1996), in correspondence with other experiments on high-T_c materials. The identification of the actual pinning mechanism with some of the theoretically predicted ones is therefore still impossible.

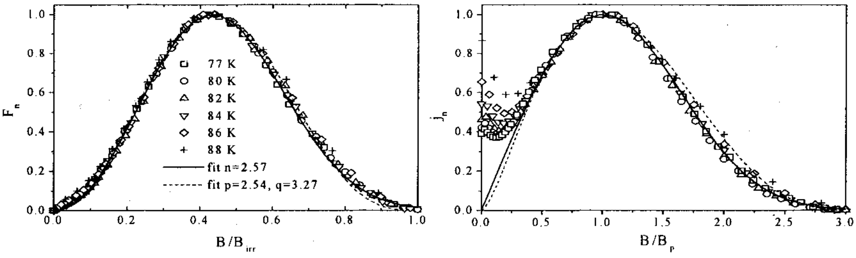

Fig. 3 The experimental data measured on the Nd-123 single crystal by means of SQUID, represented in terms of pinning force density (a) and critical currents (b). The full lines in (a) and (b) are the fits by means of eq. (5) and (3), respectively, with m=1, n=2.57, and b_{pirr}=0.43. The dashed lines represent the fit by means of eqs. (7) and (8), respectively, with p=2.54 and q=3.27.

SUMMARY

In conclusion, we discussed properties of the exponentially decaying functions following from the concept of thermally activated creep on a logarithmic pinning potential. These functions were compared with the power-law functions developed for conventional superconductors. We showed that both types of functions give satisfactory fits to the peak effect observed in RE-123 materials. The fitting parameters of the power-law functions are, however, rather high, above the limits given for different pinning mechanisms in conventional superconductors. A direct identification of the actual pinning process with some of the theoretically proposed mechanisms is not yet possible. A further theoretical and experimental work is needed to correlate these empirical expressions (either exponentially decaying or power-law) with the microscopic processes standing behind FE.

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