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Comparison between critical current density in thin superconducting films estimated from temperature and field dependence of ac susceptibility

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ABSTRACT

We have measured an ac magnetic susceptibility of recent second generation high temperature superconductor wires (coated conductor tapes) both as a function of an amplitude of an applied ac magnetic field at fixed temperatures and as a function of temperature at the fixed amplitudes. We find that data acquired by both methods are well described by ac susceptibility calculated on the basis of the Clem–Sanchez model to a response of thin superconducting disks in the Bean critical state to an applied perpendicular ac magnetic field. We show how to link the empirical data dependent on the field amplitude or temperature with theoretical data dependent on the ratio between the critical current density and field amplitude. The critical depinning current densities and its temperature dependence found by both methods are in good agreement. We discuss and compare accuracy and time saving of both methods.

1. Introduction

Thin superconducting films are fundamental materials both for superconducting electronics and wires. Low noise sensors as well as wires capable of high transport currents and operation in strong magnetic fields are based on materials with strong vortex pinning. In the case of sand-pile like quasistatic behavior of the magnetic flux described by the Bean model [1] a complete analytical model for magnetization curves of thin disks in a perpendicular applied ac magnetic field is known [2–4]. Numerical calculations show that this Clem–Sanchez model (CSM) may also be applied well to squares and rectangles as a difference in a shape of the magnetization curves is less than 1% [5]. On the basis of these magnetization loops the fundamental and harmonics of the complex ac magnetic susceptibility are calculated as a function of an applied field amplitude, critical depinning current density and film thickness. On the other hand, the experimental ac magnetic susceptibility usually is measured as a function of sample temperature at the fixed ac field amplitude or as a function of the ac field amplitude at fixed temperature. As it implies, fitting of the theoretical (following CSM) ac susceptibility dependence on the ac magnetic field with experimental data allows a contactless technique which provides the critical current density and its temperature dependence. We show that measurements of both the temperature dependence at the fixed ac field amplitudes or the ac field amplitude dependence at fixed temperatures give the same critical current density and its temperature dependence, i.e. an identical critical surface as well as critical-state behavior.

Second generation of high temperature superconductor (2G HTS) wires (coated conductor tapes) based on (RE)$Ba_2Cu_3O_{7-x}$ (REBCO, RE = rare earth) thin films has much more favorable flux pinning conditions at high temperatures compared with first generation based on Bi–Sr–Ca–Cu–O. The wires demonstrate superior performance in a magnetic field, a property believed to be due to the nano-scale flux pinning centers created through the use of a rare earth element substitution in the materials [6–9]. Strong flux pinning prevents flux from diffusion (creep) and flow even near a critical temperature and response to an applied magnetic field is frequency independent which is an example of a critical-state in type-II superconductors described by the Bean model [1].

2. Materials and methods

Samples of 4 mm long segments are cuts from the 4 mm wide coated conductor tapes of the brands SCS4050 and SCS4050-AP produced by SuperPower Inc. The SCS4050 wire contains (Sm-Y) in MOCVD made 1 μm thick REBCO layer [6]. Recently, improvements

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have been made in the J_c vs. magnetic field angle performance of the 2G HTS wire through the replacement of Sm with Gd in the REBCO composition [8], as well as the inclusion of Zr into the REBCO structure [9]. The SCS4050-AP wire has improved pinning by Zr doping of MOCVD made 1.1 μm thick REBCO layer [10]. With higher dopant levels a nano-defect density increases and thereby pinning while critical temperature slightly decreases [9].

Measurements of the ac susceptibility were done using a non-commercial continuous reading SQUID magnetometer [11,12]. A sample is stationary both in pick-up coils of gradiometric configuration (a pair of coils wound in series opposition) and solenoid during measurements that avoids the problems involved with moving the sample [13].

A control software allows us to switch between the measurement of: (a) temperature dependence of the ac susceptibility at fixed ac field amplitude, frequency and dc field, (b) magnetization loops at a triangular or sinusoidal field sweep at fixed temperature with an optional simultaneous measurement of the ac susceptibility, (c) relaxation of the magnetic moment induced by a field step or pulse, etc. Recently, we wrote in a software code for the ac susceptibility measurement as a function of the ac field amplitude at fixed temperature.

The sample is placed in a sample space of an anti-cryostat in a ^{4}He gas environment. Temperature of the sample space is measured using the Lake Shore SD-470 Si diode sensor and controlled using the Cryo-con model 34 temperature controller and resistive wire heater. The sample temperature is measured with the Lake Shore TG-120PL GaAlAs diode sensor mounted on the top of the cylindrical sapphire holder while the sample is mounted on the bottom. The sensors are not calibrated to mK accuracy but their sub mK resolution and control loop allow temperature stability and reproducibility of the order of 1 mK at 100 K.

An applied field is generated by a superconducting solenoid operating in a non-persistent mode. The solenoid is supplied from a current source driven by voltage on the output DACs of National Instruments PCI-4451 card [14].

Both SQUID output signal $M(t)$ and voltage $H(t)$ monitoring the current to the superconducting solenoid are simultaneously digitally sampled using the input ADCs on the PCI-4451, recorded on a hard disk and real time processed [12]. Usually 2.56 s long segments of the record are Fourier transformed to a frequency domain. Data in the segment are shifted by one fourth of the segment and vacant part is updated in period of 0.64 s, temperature is read in the process and segment is Fourier transformed. Applied ac field periods are a fraction of 2.56 s, i.e. frequencies are multiples of 0.390625 Hz.

With the applied field $H(t) = H_{ac}\cos(2\pi ft)$, where H_{ac} is the amplitude and f is the frequency, the nth harmonic of the complex ac susceptibility is given by

$$\chi_n = \frac{\mathcal{M}(nf)}{H_{ac}\exp(ni\varphi)}, \tag{1}$$

where $\mathcal{M}(f)$ is the Fourier transform of $M(t)$ and the complex $H_{ac}\exp(ni\varphi) \equiv |\mathcal{H}(f)|\exp(ni\arg\mathcal{H}(f))$ takes into account a phase of the Fourier component $\mathcal{H}(f)$ of the applied field, i.e. a time shift between a Fourier transformed data segment record and cosine field [12].

The ac field amplitude dependence of the ac susceptibility was measured for fixed temperatures and ac field frequencies while the ac field amplitude was swept exponentially from 0.2 μT to 200 μT in 1000 steps during 640 s. The temperature dependence of the ac susceptibility was measured for fixed amplitudes and frequencies of the applied ac field at cooling or warming rate of 1 K/min or 2 K/min.

3. Calculation

The theoretical magnetization curves $M(H)$ are computed using the Clem–Sanchez complete analytical model for the magnetic moment of thin disks in a low-frequency oscillating perpendicular magnetic field [4]. The model applies to a critical-state described by the Bean model [1] in disks of thickness $d \ll R$, where R is the disk radius, and either that $\lambda \leqslant d$, where λ is the London flux penetration depth, or, if $d < \lambda$, that 2D screening length $\Lambda = 2\lambda^2/d \ll R$ [15]. The magnetization curves are a function of H_d/H_{ac}, where $H_d = J_c d/2$ is the characteristic field and J_c is the critical depinning current density. We calculate the magnetization curves numerically for a set of discrete values of H_d/H_{ac}. The fundamental and harmonics of the complex ac susceptibility χ are calculated by Eq. (1) as well as the experimental susceptibility [12].

When the experimental ac susceptibility is measured as a function of the field amplitude the experimental data $[\mu_0 H_{ac}, \chi]$ are fitted to the data $[H_{ac}/H_d, \chi]$ calculated on the basis of the model using the single adjustable parameter $a = \mu_0 H_d$,

$$\left[a\frac{H_{ac}}{H_d}, \chi\left(\frac{H_d}{H_{ac}}\right)\right] \leftrightarrow [\mu_0 H_{ac}, \chi(H_{ac})]. \tag{2}$$

The parameter a yields the critical current density $J_c = 2a/\mu_0 d$ at the fixed sample temperature.

In the case of temperature dependence of the experimental susceptibility the experimental data $[T, \chi]$ are fitted to the theoretical data $[H_d/H_{ac}, \chi]$ to find the critical current density and its temperature dependence [12]. A procedure proceeds from the assumption that the temperature dependence of the critical current density is a monotonically decreasing function of temperature,

$$\frac{J_c(T)}{J_c(0)} = \frac{H_d(T)}{H_d(0)} = \left(1 - \left(\frac{T}{T_c}\right)^m\right)^n, \tag{3}$$

where n and m are exponents and T_c is the critical temperature. We define "effective temperature" using the inverse function for Eq. (3),

$$\left(\frac{T}{T_c}\right)_{effective} \equiv \left(1 - \left(c\frac{H_d}{H_{ac}}\right)^{\frac{1}{n}}\right)^{\frac{1}{m}}, \tag{4}$$

where $c \equiv H_{ac}/H_d(0)$, n, m, and T_c are adjustable parameters that fit the experimental susceptibility to the susceptibility calculated on the basis of the model

$$\left[\left(\frac{T}{T_c}\right)_{effective}, \chi\left(\frac{H_d}{H_{ac}}\right)\right] \leftrightarrow \left[\frac{T}{T_c}, \chi(T)\right]. \tag{5}$$

This results in zero temperature critical current density

$$J_c(0) = 2H_{ac}/cd \tag{6}$$

and temperature dependence $J_c(T)$ given by Eq. (3).

Often, the critical current density is estimated only using the peak in the imaginary part of the fundamental susceptibility χ_1'' or wide-band susceptibility [16]. For disks the $\max(\chi_1'')$ occurs at the field amplitude $H_m = H_{ac} = 1.943H_d$, where $\max(\chi_1'') = 0.2408$ and real part of the fundamental susceptibility takes value of $\chi_1' = -0.3801$. Total susceptibility is $\chi\chi_0$, where χ_0 is the magnitude of the ideal Meissner susceptibility of the disk, $\chi_0 = 8R/3\pi d = 0.8488R/d$ [17]. This yields the critical current density $J_c = 2H_d/d = 1.0293H_m/d$.

Numerical calculations show that for the square films of the side s is $\max(\chi_1'') = 0.24$, $\chi_1' = -0.378$, $\chi_0 = 0.4547s/d$, and $J_c = 1.0977H_m/d$ which is about 7% higher then for disks of the same thickness [17].