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On the thermodynamic critical field in MgB_2 superconductor

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Abstract

The thermodynamic critical field H_c has been obtained from the equilibrium magnetization of MgB_2 superconductor. The entire hysteresis loops have been found to scale with H_c such that the M/H_c, curves follow closely universal behavior over a wide temperature range. The peaks in the pinning force curves have been found to scale with the vortex line energy as $(H_c)^2$. Moreover, the positions of the normalized $F_{p(max)}$ occur at about $0.1H_{irr}$ significantly lower than what is expected from Dew-Hughes model.

Keywords: Flux pinning; Reversible magnetization; Scaling behavior

1. Introduction

Since the discovery of superconductivity in MgB_2 [1], major effort has been devoted towards understanding the basic physical properties of this binary intermetallic compound. The simplicity of the structure and the relative ease of preparation have clear advantage in probing various aspects of the BCS theory at intermediate transition temperatures in this old new superconductor [2]. For example, the Boron-isotope effect has revealed the importance of phonon frequencies [3]. Moreover, thermodynamic properties, transport measurements and the phonon density of states strongly suggest that MgB_2 is likely to be a phonon-mediated s-wave superconductor [4–8]. Recent Raman spectroscopy agrees with the strong-coupling calculations and supports the conventional electron–phonon coupling mechanism [9].

In an attempt to sort out the fundamental mechanisms responsible for pinning in borocarbides [10], stripe phase superconductors [11] and other high temperature superconductors [12], we have recently proposed using the thermodynamic critical field H_c (rather than H_{irr}, H_{max} or H_{c2}) as a single scaling parameter. In this analysis, pinning force has been scaled by the condensation energy $\sim(H_c)^2$ and represented versus H/H_c. Moreover, the peak in the pinning force $F_{p(max)}$ has been found to scale with the energy of the single vortex $\sim(H_c)^2$. In this approach, we avoid determining H_{c2} and extend the applicability of pinning theories to a very low fields, near H_c where, $H_c = H_{c2}/\kappa\sqrt{2}$.

Recently, Willemin et al. have confirmed that the reversible magnetization is indeed close to the average value of the magnetization. Willemin et al. used a small transverse ac field to 'shake' the vortex lattice out of the non-equilibrium to the equilibrium 'reversible' configuration [13]. Hence, one can use the equilibrium magnetization to evaluate H_c over a much wider field and temperature range.

Such an approach has been recently used to evaluate H_c for MgB_2, polycrystalline [4] and single crystal [14] over a temperature range that extends much below the reversible magnetization range.

In this paper, the equilibrium magnetization is used to evaluate the thermodynamic critical field (H_c) and used it in a systematic way to study the scaling behavior in MgB_2 superconductor using H_c as a single scaling parameter. Namely, the entire hysteresis loops and the peaks in the pinning force [$P_{f(max)}$]. Scaling of the $P_{f(max)}$ with H_{irr} is also presented and compared with our approach.

2. Experimental technique

Appropriate amounts of shiny Mg (99% purity) strips and B (99.5% purity) coarse powder were mixed and wrapped in

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a Ta sheet, under Ar-gas. The sample was sealed under Ar-gas in stainless steel tube and annealed under Ar-gas flow at 950 °C for 2 h. The tube was water-quenched to room temperature. Magnetization measurements were performed on a 9-Tesla PAR-4500 vibrating sample magnetometer (VSM). The magnetic moment was calibrated using a standard Ni-sample and the temperature was monitored using a calibrated carbon-glass resistor.

3. Results and discussion

The free energy is commonly evaluated using the area under the reversible ‘equilibrium’ magnetization M_{eq} using $\int M_{eq}\,dH = -(H_c)^2/8\pi$, where M_{eq} can be obtained using Bean’s relation; $M_{eq} = (M_1 + M_2)/2$, M_1 and M_2 are the descending and ascending branches of the hysteresis loop. Here H_c is the thermodynamic critical field.

The hysteresis loop and the evaluated equilibrium magnetization obtained at 30 K is presented in Fig. 1a. The inset of Fig. 1 shows the susceptibility changes with temperature. The graph reveals that the superconducting volume fraction near 4 K is almost 100% and the transition temperature is ~39 K (T_{on}).

The free energy data has been used to evaluate H_c, the thermodynamic critical field, in the temperature range 4–37 K. The results are presented versus $(1 - t^2)$ on log–log scale in Fig. 1b. Here $t = T/T_c$ is the reduced temperature.

The irreversibility field H_{irr} is taken as the field at which ΔM drops within the resolution of our VSM (~10^{-5} emu). The H_{irr} values are also presented in Fig. 1b.

The H_{irr} and H_c curves are nearly parallel indicating that both fields vary as $\sim(1 - t^2)^{\alpha}$ with $\alpha \approx 3/2$. The exponent value for H_{irr} field is what one expects from 3D flux creep in high temperature superconductors [15]. Similar behavior has been recently found for MgB_2 thin film [16].

The fitted H_c data yield: $H_0 = 5.58$ kOe and $dH_c/dT \approx 0.220$ kOe/K at T_c (~39 K) and $\alpha \approx 1.55$ deviating from $\alpha \approx 1$ expected from the two fluid model. Reanalyzing the Finnemore et al. measurements for H_c we obtain $\alpha \approx 1.2$, however these data are very close to T_c [4].

It is interesting to note that there is a spread in the reported value of H_0 in various MgB_2 samples. It ranges between 2.80 kOe for single crystal [14] and 6.5 kOe for polycrystalline [4]. However, the ratio H_0/T_c remains close to 0.140 kOe/K, which is about half the ratio obtained for the classic Nb superconductor.

Using the electronic specific heat coefficient $\gamma \approx 2.53$ mJ/K^2 [2], we obtain for the ratio $\gamma(T_c/H_0)^2 \approx 1.30$ which is much larger than what the BCS theory predicts (≈0.17) for conventional superconductors [2,17]. The quantity $\gamma(T_c/H_0)^2$ can also be used to evaluate the “*lower*” energy gap, we have;

$$\left(\frac{\Delta(0)}{kT_c}\right)^2 = \left(\frac{\pi}{6}\right)\gamma\left(\frac{T_c}{H_0}\right)^2 = 0.402 \qquad (1)$$

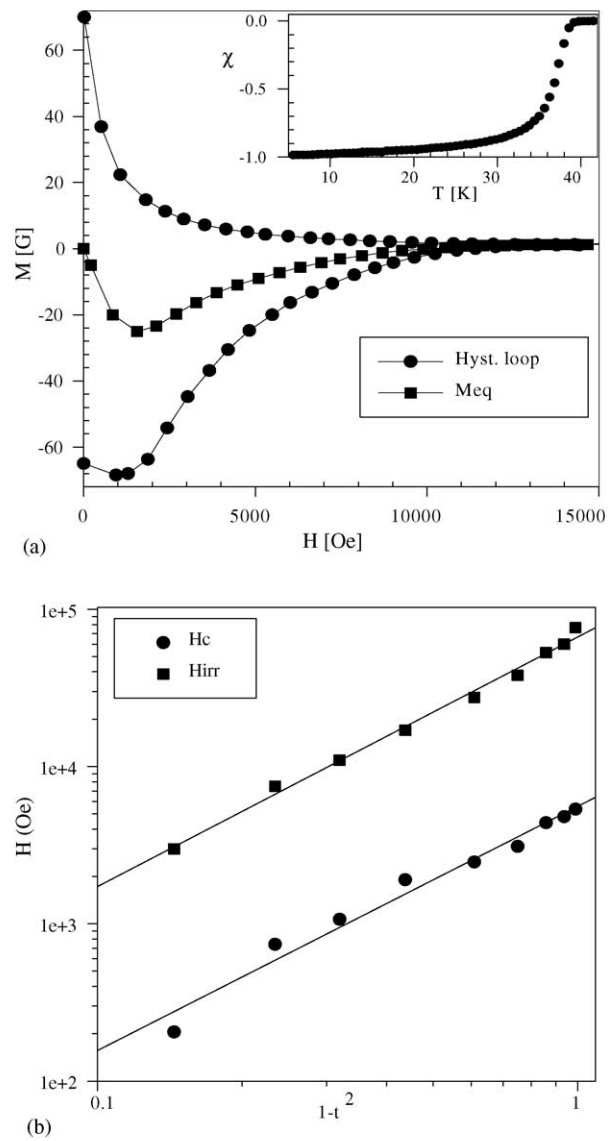

Fig. 1. (a) Hysteresis loop and the equilibrium magnetization at $T = 30$ K obtained using Bean’s model. Inset susceptibility changes with temperature. (b) Variations of the thermodynamic critical field and the irreversibility field with $(1 - t^2)$. The solid line is the best linear fit.

$$\frac{2\Delta(0)}{kT_c} = 1.27 \qquad (2)$$

The result of Eq. (2) is about half what is expected from BCS theory. This gives a “lower” energy gap $(2\Delta(0)) \sim 4.37$ meV in close agreement with tunneling measurements of Bader and Ng [18] and Raman spectroscopy data [9].

In Fig. 2 we present the hysteresis loops normalized by the thermodynamic critical field as $M_n = M/H_c$ versus $h_n = H/H_c$. The loops for $T = 4$–33 K follow nearly a single hysteresis loop. The position of the minima for all temperatures falls at about $h = 0.5$ ($H = 0.5\,H_c$), though its amplitude is reduced significantly at 33 K. The descending branches closely fall on a single upper branch of the universal loop. Moreover,