Journal of Magnetism and Magnetic Materials 329 (2013) 84–87

Contents lists available at SciVerse ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Magnetic hysteresis scaling in thulium: Implication of irreversibility-related scaling for soliton wall motion in an Ising system

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ARTICLE INFO

Article history:
Received 31 May 2012
Received in revised form
28 September 2012
Available online 13 October 2012

Keywords:
Magnetic hysteresis
Scaling
Rare earth metal
Universality
Magnetic domain wall

ABSTRACT

We report low-field magnetic hysteresis scaling in thulium with strong uniaxial anisotropy. A power-law hysteresis scaling with an exponent of 1.13 ± 0.02 is found between hysteresis loss and remanent flux density of minor loops in the low-temperature ferrimagnetic phase. This exponent value is slightly lower than 1.25–1.4 observed previously for ferromagnets and helimagnets. Unlike spiral and/or Bloch walls with a finite transition width, typical for Dy, Tb, and Ho with planar anisotropy, a soliton wall with a sudden phase shift between neighboring domains may dominate in Tm due to its Ising-like character. The observations imply the presence of universality class of hysteresis scaling that depends on the type of magnetic anisotropy.

1. Introduction

The study for domain-wall motion in magnetic materials is of great technological and fundamental physical importance, as it predominates the magnetic quality of future electric devices as well as diverse magnetic phenomena [1,2]. In an external magnetic field, domain walls show a sequence of discrete jumps and the irreversibility of wall motion due to pinning fields results in a hysteresis and a power-law loss behavior. In the case of bulk magnets, several empirical hysteresis scaling for hysteresis parameters have been observed to date [3]. In particular, recent experiments showed a power-law scaling law which relates the hysteresis loss with remanent flux density with an exponent of 1.3–1.4 [3]. In contrast to the traditional Steinmetz equation for bulk soft ferromagnets [4], the scaling law universally holds true also for semi-hard ferromagnetic materials, in which another magnetization mechanisms (reversible wall motion, magnetization rotation) coexist with irreversible Bloch wall motion. Further, the very close exponent was quite recently obtained in the helical magnetic phase with spiral domain walls for rare-earth metals Dy, Ho, and Tb [5,6]. The results demonstrated a possible existence of a universal mechanism of irreversible wall motion, independent of the types of domain walls.

In this paper, we report observations of magnetic hysteresis scaling for a heavy rare-earth metal Tm. Owing to its very strong uniaxial anisotropy, Tm can be regarded as a model system of the so-called axial-next-nearest-neighbor-Ising (ANNNI) model, which has been extensively studied theoretically to explain sinusoidally modulated structures [7,8]. For Tm, a soliton wall, which separates commensurate magnetic regions, is considered to dominate the magnetic phase. Unlike Bloch and spiral walls with a finite transition region in which magnetic moments rotate [9,10], the soliton wall will behave as a kink at low temperatures, associated with a sudden 'phase shift' between neighboring domains. Below $T_N \sim 58$ K, Tm exhibits a sinusoidally modulated incommensurate magnetic (ICM) structure with magnetic moments along the hexagonal *c*-axis [11–13]. With decreasing temperature, the propagation wave number along the *c*-axis, q_c, slightly increases and magnetic moments along the *c*-axis are squared-up below $T \sim 40$ K. At low temperatures below $T_c \sim 30$ K, a ferrimagnetic (FR) structure with $q_c = \frac{2}{7}$ where three layers with moments pointing down along the *c*-axis are followed by four layers with moments pointing up, takes place. This yields a net magnetic moment of $\sim 1.0\ \mu_B$/atom along the *c*-axis. Here, we show that there exists a power-law hysteresis scaling in the FR phase, whose exponent value implies the presence of the universality class depending on the anisotropy.

2. Experimental

A polycrystalline sample of Tm with a purity of 99.9% was used. Our x-ray diffraction measurements at room temperature confirmed a hexagonal close-packed structure of a space group of $P6_3/mmc$ with the lattice constant of $a = 3.542(1)$ Å and $c = 5.566(1)$ Å, being consistent with previous investigations [12]. No significant preferred orientation was detected. As shown by

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0304-8853/$ - see front matter
http://dx.doi.org/10.1016/j.jmmm.2012.10.009

our dc magnetization measurements at $T=5$ K with a superconducting quantum interference device (SQUID) magnetometer (Quantum Design MPMS-XL), Tm exhibits a magnetization plateau at fields below ~ 1.6 MA/m with ~ 0.5 μ_B/atom along the field direction. This moment value corresponds to that of the FR structure for a polycrystalline Tm sample with randomly oriented grains, associated with strong uniaxial anisotropy, which confirmed an onset of the FR structure at low temperatures in the present sample.

For study of a magnetic hysteresis scaling, a toroidal sample with external and internal diameters of 9 and 7 mm, respectively, and thickness of 5 mm was prepared. Flux-density (B)–field (H) loops were measured with a conventional fluxmetric method [5]. A 178-turn exciting and 100-turn detecting coils of copper wires were wound around the sample to generate a cyclic magnetic field in the circumferential direction and pick up the induced voltage due to magnetization, respectively. B–H loops with various field amplitudes H_a up to ~ 30 kA/m were measured by step-by-step increasing H_a, maintaining the speed of applied field dH/dt. The results did not show any dH/dt dependence in the range of 16–64 kA/m/s and the results for dH/dt=64 kA/m/s will be given in this study. The temperature dependence was measured at intervals of 1 K on both heating and cooling with the temperature stability of 0.05 K.

3. Results and discussion

Fig. 1 shows a set of B–H loops with various field amplitude H_a, taken at various temperatures on heating at around T_c. For each loop with different H_a, the parameters B_a^*, B_R^*, and W_F^*, defined as those in the inset in Fig. 1, were obtained. In Fig. 2, the temperature dependence of minor-loop initial permeability μ_m, taken on heating and cooling, is given. Here, μ_m was obtained from a linear part of $B_a^*-H_a$ curves for B_a^* below 3×10^{-2} T. From local maxima of μ_m^*, T_N and T_c were determined; $T_N=53$ K, and $T_c=25.5$ K and 19.5 K for heating and cooling, respectively. A thermal hysteresis of about 6 K for μ_m was observed at around T_c, while no thermal hysteresis was detected at around T_N.

As shown in Fig. 1, the reversible magnetization process largely contributes to magnetization up to the maximum field of 30 kA/m and $B-H$ hysteresis loops due to an irreversible process are sheared below T_c. With increasing temperature, the loop width gradually develops, maximizes just below T_c, and was largely reduced after the onset of the ICM phase at T_c. The hysteresis loss remains just above T_c and almost disappears at $T=29$ K. As the temperature decreases from a temperature above T_N, the hysteresis loss shows up at around 23 K just above T_c and gradually develops with temperature. The hysteresis loss in the ICM phase was observed up to T_c+4 K for both the heating and cooling process.

Fig. 3 shows a double logarithmic plot of $W_F^*-B_R^*$ curves, taken at various temperatures on heating. The curves exhibit a straight lines in a wide B_R^* range over two orders of magnitude below T_c. Even just above T_c the linear behavior seems to persist, keeping almost the slope constant. With increasing temperature from a temperature below T_c, the curves shift downwards and then start to shift upwards at around T_c. The linear behavior observed on a double logarithmic scale indicates a power-law scaling for the $W_F^*-B_R^*$ curves.

In order to extract hysteresis scaling properties due to an irreversible mechanism, the observed curves were least-squares

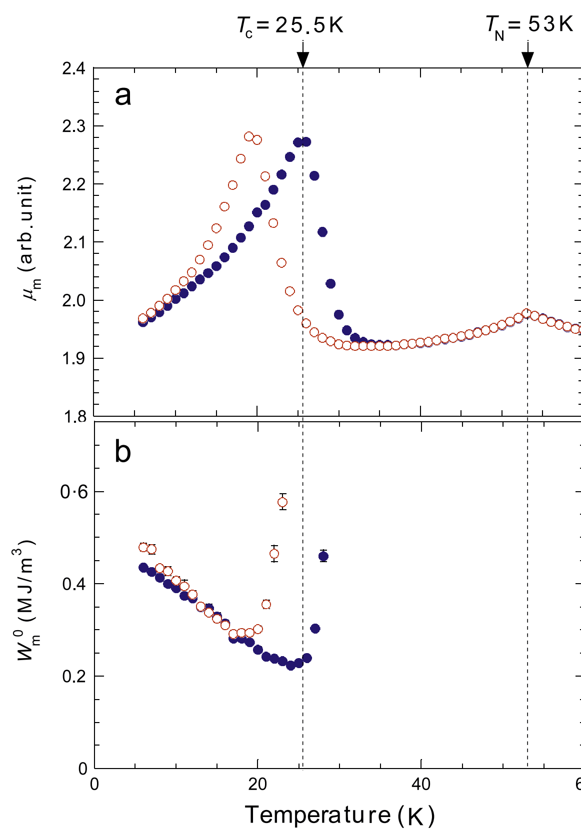

Fig. 2. (a) Minor-loop initial permeability μ_m and (b) coefficient of a scaling power law, W_m^0 as a function of temperature. The solid and open circles represent the data taken on heating and cooling, respectively.

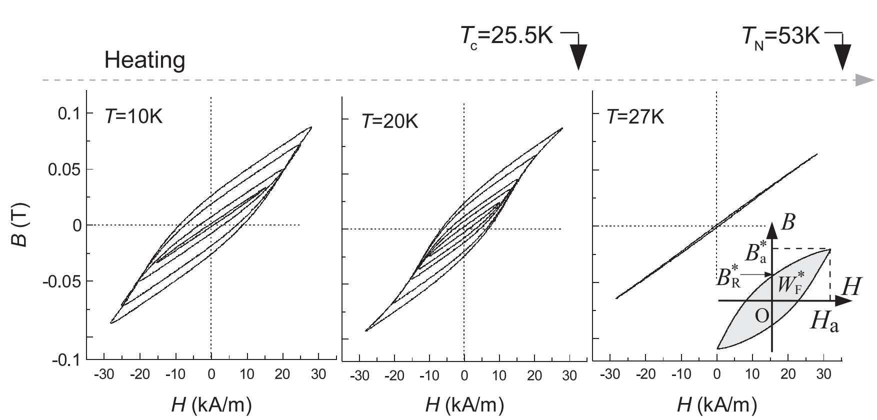

Fig. 1. B–H loops with various field amplitudes H_a, taken at different temperatures on heating; 10 K and 20 K below T_c and 27 K above T_c. The inset shows the parameters of a B–H loop; B_a^*, B_R^*, and W_F^* are the maximum flux density, remanent flux density, and hysteresis loss, respectively.