Journal of Alloys and Compounds 720 (2017) 388–394

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Hysteresis properties of a quenched disordered binary alloy cylindrical nanowire: A Monte Carlo simulation study

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ARTICLE INFO

Article history:
Received 27 March 2017
Received in revised form
21 May 2017
Accepted 24 May 2017
Available online 27 May 2017

Keywords:
Binary alloy systems
Magnetic nanowire
Hysteresis
Monte Carlo simulation

ABSTRACT

We have elucidated the hysteresis features of a quenched disordered binary alloy cylindrical nanowire of the type A_pB_{1-p} by means of Monte Carlo simulation technique. The nanowire system is composed of two types of magnetic components, A with spin-1/2 and B with spin-1, which are distributed randomly on the sites of the nanowire. The dependence of the remanence magnetization (M_r) and coercivity field (H_c) values on the active concentration of type-A magnetic components, p, and the strength of the spin-spin coupling between type-A and -B components have been investigated in a wide range of temperature values. Our Monte Carlo simulation findings suggest that, it is possible to enhance the magnetic properties (i.e., coercivity, remanence as well as hysteresis loops) of the system by changing the concentration of the magnetic components, and also the exchange coupling strength between unlike atoms. Finally, we compare our numerical findings with recent experimental results, and it is found that there exists a qualitatively agreement between them.

1. Introduction

In the last several decades, there has been a remarkable interest on nanostructured magnetic materials not only due to their wide range of technological applications but also because of their outstanding magnetic features, for instance superparamagnetism [1,2], giant magnetoresistance [3,4] and exchange bias effect [5,6]. Among these, one-dimensional nanostructured magnetic nanowires play an important role in nanoscience owing to their unique properties such as large proportion of surface atoms and high length to diameter ratio [7]. Besides, ferromagnetic nanowires provide promising application areas ranging from high density magnetic recording media [8,9] to permanent magnets [10,11].

From the experimental point of view, much attention has been paid to the binary alloy magnetic nanowire arrays fabricated in nanoporous anodic aluminum oxide matrix by electrochemical deposition techniques. The alloy composition and geometrical properties such as nanowire length and diameter can be tuned experimentally making it possible to control the magnetic properties of nanowires [12–14]. In a recent study, Ramazani and co-workers have investigated the effects of geometrical parameters on the magnetic features of FeNi nanowire arrays [15]. Their hysteresis loop measurements show that with an increment of nanowire length and diameter, the coercivity and squareness values decrease. Moreover, several experimental studies have been reported the effects of concentration value, p, on the magnetic features of binary alloy nanowire arrays of the type A_pB_{1-p} [16–19]. For instance, in Ref. [19], it has been observed that changing Ni content of Co_pNi_{1-p} nanowire arrays enables to control magnetic properties like coercive field and the remanent magnetization.

On the other side, it is a fact that the experimental results have stimulated theoretical studies regarding the hysteresis characteristics of magnetic nanowires. Mostly, magnetic nanowires with core-shell morphology have been investigated with several methods such as effective field theory (EFT) [20–25] and Monte Carlo (MC) simulations [26–32]. Magnetic properties of cylindrical spin-1/2 core-shell Ising nanowire have been investigated within the framework of EFT [20] and MC simulations [26]. For both methods it has been found that for appropriate values of system parameters, triple hysteresis loops occur in the presence of antiferromagnetic interaction between shell and the core parts of the system. In another interesting work, magnetic and thermodynamic properties of mixed-spin Ising nanowire with spin-1 core and spin-3/2 shell has been studied in the framework of MC simulation [29,30]. The authors have stated that the single-ion anisotropy, exchange coupling strength between the core and the shell and the temperature have considerable influences on the coercivity and

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http://dx.doi.org/10.1016/j.jallcom.2017.05.254
0925-8388/

remanence of the system. The effects of random crystal field on the hysteresis features of a spin-1 ferromagnetic cylindrical nanowire has been investigated by Zaim and co-workers in Ref. [31] by using MC technique. Single, double or para hysteresis loops are observed depending on the parameters of the random crystal field and temperature. Hysteresis properties of magnetic nanowires in the presence of random magnetic field [22] and transverse field [23] have been examined within the framework of EFT. Besides, more realistic core/shell nanowires are simulated by micromagnetic simulations. For instance in Ref. [33], exchange bias properties of core/shell coaxial Co/CoO freestanding nanowires have been studied in the presence of cooling and external magnetic fields in the perpendicular nanowire axis.

In our previous work, we have elucidated the magnetic phase transition properties of a quenched disordered binary alloy cylindrical nanowire system by means of MC simulations [32]. The phase diagrams of the system are obtained in several planes. However, to the best of our knowledge, there is no theoretical report on hysteresis properties of a binary alloy magnetic nanowire. Therefore, in the present study, we intend to investigate magnetic features of a single ferromagnetic quenched disordered binary alloy cylindrical nanowire system of the type A_pB_{1-p} where p represents the active concentration of type-A atoms. The nanowire contains two types of magnetic components A with spin-1/2 and B with spin-1 and they are distributed randomly on the lattice of the nanowire. With MC simulation technique based on Metropolis algorithm, we determine the dependence of magnetic properties such as, coercivity, remanence and hysteresis loops, on the concentration value of the type-A magnetic components and temperature for several values of the exchange coupling between type-A and type-B magnetic components.

The paper is organized as follows. In section 2, the details of the theoretical model and our MC simulations are given. The results of our numerical simulations are presented in section 3. Finally, our conclusions are summarized in section 4.

2. Formulation

We implement quenched disordered binary alloy cylindrical nanowire of the type A_pB_{1-p} with total radius r, and length L. The magnetic components A and B are randomly located on the magnetic nanowire with the concentration p and $1-p$, respectively. Thus, there exists three types of exchange interactions in the nanowire: J_{AA}, J_{BB} and $J_{AB} = J_{BA}$ between $A-A$, $B-B$ and $A-B$ atoms, respectively. The Hamiltonian of the studied system is defined as follows:

$$\widehat{H}_{total} = \widehat{H}_{ex} + \widehat{H}_{anisotropy} + \widehat{H}_{Zeeman}, \tag{1}$$

here $\widehat{H}_{ex}, \widehat{H}_{anisotropy}$ and $\widehat{H}_{Zeeman}$ terms denote the energy contributions to the system coming from spin-spin interaction between nearest-neighbor spins, single-ion anisotropy and Zeeman terms, respectively. They are given as follows:

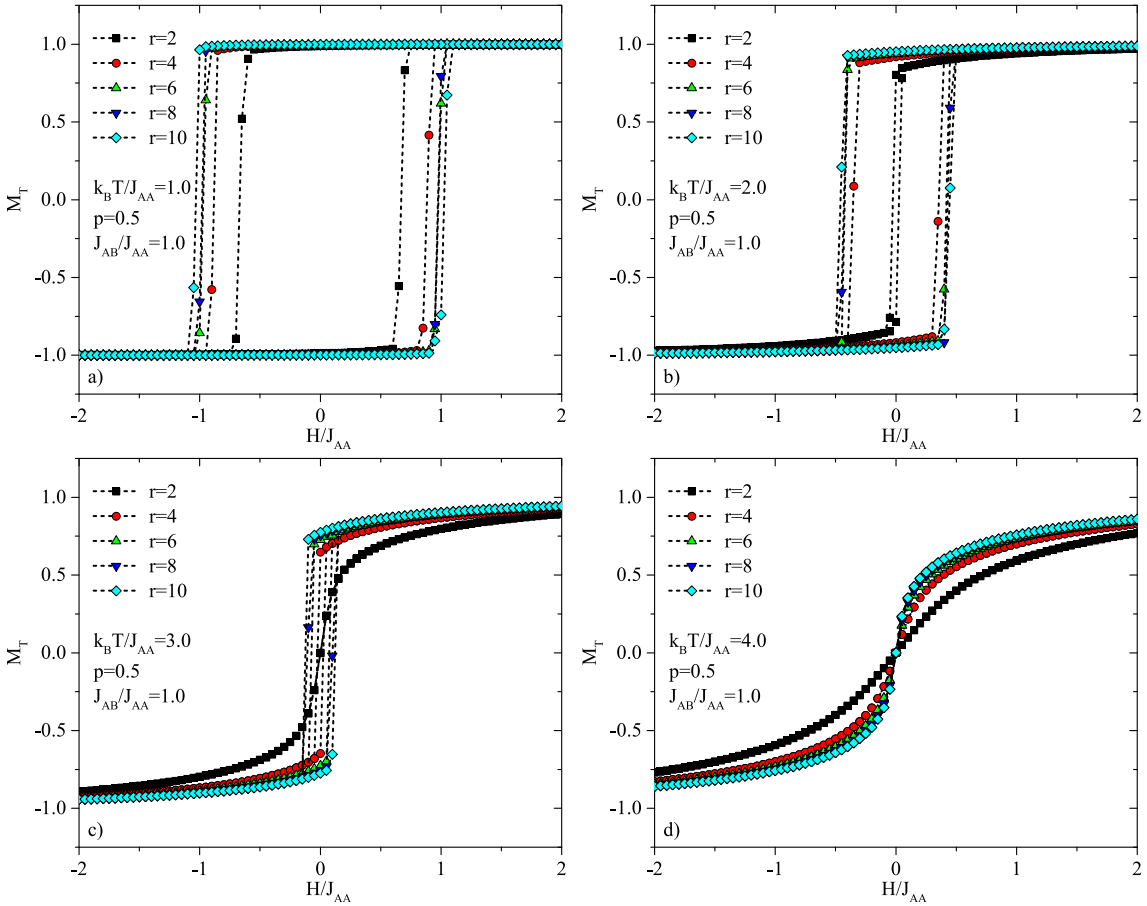

Fig. 1. Hysteresis loops of the binary alloy cylindrical nanowire for several values of the nanowire radius, r=2,4,6,8,10 with p=0.5 and $J_{AB}/J_{AA} = 1.0$ at a) $k_BT/J_{AA} = 1.0$, b) $k_BT/J_{AA} = 2.0$, c) $k_BT/J_{AA} = 3.0$ and d)$k_BT/J_{AA} = 4.0$.