Journal of Magnetism and Magnetic Materials 389 (2015) 40–47

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Non-equilibrium phase transition properties of disordered binary ferromagnetic alloy

Erol Vatansever [a,b,*], Umit Akinci [a], Hamza Polat [a]

[a] Department of Physics, Dokuz Eylül University, Tr-35160 İzmir, Turkey
[b] Dokuz Eylül University, Graduate School of Natural and Applied Sciences, Turkey

ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form
21 March 2015
Accepted 9 April 2015
Available online 11 April 2015

Keywords:
Dynamic phase transitions
Disordered binary alloy
Multi-critical phenomena
Effective-field theory

ABSTRACT

Non-equilibrium dynamic phase transition features of a disordered binary ferromagnetic alloy consisting of spin-1/2 and spin-1 components under the presence of a time dependent oscillating magnetic field have been analyzed for a two dimensional square lattice. With the help of Glauber-type stochastic process, the kinetic equations of time dependent magnetizations have been derived based on the effective-field theory with single-site correlations. A systematic analysis for the whole range of the concentrations of randomly distributed components as well as other system parameters has been carried out. According to our numerical investigations, the considered system presents unusual thermal and magnetic field behaviors such as the existence of dynamic multi-critical behavior and also boundaries of the coexistence region, where both dynamically ordered and disordered phases overlap, sensitively depends on the studied parameter space.

1. Introduction

Investigation of binary magnetic system including disorder effect problems which may be originated from random exchange interactions between two different types of magnetic components (denoted as *A* and *B*) or from a random distributions of the magnetic atoms depending on the relative concentrations on the magnetic materials has a long history, and there have been a great many studies focused on disordered magnetic materials with quenched randomness where the random variables of a magnetic system may not change its value over time. From the experimental point of view, a number of studies with the site or bond randomness have been devoted to the better understanding of magnetic properties of different types of magnetically interacting systems such as $Rb_2Mn_cMg_{1-c}F_4$ [1], $Mn_pZn_{1-p}F_2$ [2], $Fe_pMg_{1-p}Cl_2$ [3], $Cd_{1-p}Mn_pTe$ [4], $Mn_cZn_{1-c}F_2$ [5], $Co(S_pSe_{1-p})_2$ [6], and $Co_pZn_{1-p}(C_5H_5NO)_6(ClO_4)_2$ [7].

From the theoretical point of view, a great deal of studies have been performed regarding the thermal and magnetic properties of disordered binary alloy systems containing both ferromagnetic and (or) anti-ferromagnetic spin–spin interactions, and based on the investigation of equilibrium or dynamic phase transition (DPT) properties of such types of magnetic systems, theoretical works can be classified into two basic categories. In the former group, equilibrium or static features of disordered binary magnetic systems have been analyzed by means of several types of frameworks such as Perturbation Theory (PT) [8], Mean-Field Theory (MFT) [8–11], Bethe–Peirls Approximation (BPA) [12], Effective-Field Theory (EFT) with single-site correlations [13–19] and method of Monte-Carlo (MC) Simulation [20–24]. For instance, the critical properties of random mixtures of ferromagnetic and antiferromagnetic spin–spin interactions have been studied with MC simulation on a simple cubic lattice in Ref. [20]. It has been found that the system exhibits spin-glass phase characterized by a cusp-like peak in the susceptibility. Furthermore, it is claimed by Plascak [10] that random-site binary ferromagnetic Ising model shows seven topologically different types of phase diagrams including a variety of multi-critical points within the framework of MFT.

When a magnetic system composed of interacting magnetic moments is subjected to a periodically oscillating time dependent magnetic field, the system may not respond to the external magnetic field instantaneously, hereby, which gives rise to the existence of exotic and interesting behaviors such as DPTs and unusual hysteresis behaviors due to the competing time scales of the relaxation behavior of the system and period of external magnetic field. For the first time, this type investigation regarding the DPT properties of prototype Ising model under a time dependent magnetic field has been implemented by Tomé and de Oliveira [25] within the framework of MFT. Based on this study, a typical ferromagnetic system with coupling *J* exists in dynamically disordered phase at high temperatures and for high amplitudes of

* Corresponding author at: Department of Physics, Dokuz Eylül University, Tr-35160 İzmir, Turkey. Fax: +90 232 4534188.
E-mail address: erol.vatansever@deu.edu.tr (E. Vatansever).

http://dx.doi.org/10.1016/j.jmmm.2015.04.042
0304-8853/

the periodically varying magnetic field regions. In this region, the time dependent magnetization is able to follow the external magnetic field with some delay whereas this is not the case for low temperatures and small magnetic field amplitudes. The mechanism shortly described above points out the existence of a DPT [26]. In addition to these temperature and magnetic field induced transition between ordered and disordered phases, a cooperatively interacting magnetic system can show a external field period induced DPT depending upon a selected combination of system parameters [27–30]. Besides, owing to the recent developments in experimental techniques, DPT and also hysteresis treatments can be observed experimentally [33–35]. For example, it has been shown by Berger et al. [33] that uniaxial cobalt film sample under the influence of both bias (namely time independent) and time dependent oscillating magnetic fields in the vicinity of DPT displays transient behavior for $P < P_c$, where P and P_c are period and critical period of the external applied field.

Furthermore, non-equilibrium phase transition behaviors of the mixed spin-1/2 and spin-1 model have been investigated within the several frameworks such as Dynamical Pair Approximation Method (DPAM) [36–39], MC [37–40], Cluster Variation Method (CVM) [41] as well as MFT [42,43]. For example, by benefiting from DPAM, Godoy and Figueiredo determined the phase diagrams for the stationary states of the model, and they show that it exhibits two continuous transition lines; one line between the ferrimagnetic and paramagnetic phases, and the other between the paramagnetic and anti-ferrimagnetic phases [36]. By making use of MFT formalism and Glauber-type stochastic process, DPT properties of the mixed spin-1/2 and spin-1 Ising ferrimagnetic system under a time dependent oscillating magnetic field have been studied by Keskin et al. [43], and they report that the global phase diagram of the model includes six distinct topologies and one ordered and one mixed phase. And also, the system displays one or two tricritical points and a re-entrant behavior, depending on the selected system parameters.

On the other hand, as far as we know, in the second group, there exists a limited number of non-equilibrium phase transition studies concerning disordered effects originating from different controllable physical mechanism. It is beneficial to give some examples for the sake of the completeness. Effective field investigation of DPT for site diluted Ising ferromagnet driven by a periodically oscillating magnetic field has been addressed by some of us in Ref. [31]. In such type of a system, site occupation variable can take the values $c_i = 0$ which means that the site i is empty or $c_i = 1$ if the site i is occupied by a magnetic atom. It has been shown that the system exhibits re-entrant phenomena as well as dynamic tricritical point which disappears for sufficiently weak dilution. Very recently, following the same procedure, quenched random bond diluted Ising model, where the spin–spin exchange interaction has a probability p and $1 - p$ of taking on values J and 0, respectively, has been analyzed by benefiting from the Glauber type stochastic model, and particular attention has been devoted to the better understanding of effects of bond randomness on the global phase diagrams constructed in related planes and on the microscopic origin of the magnetic system [28,32]. However, there is no attempt to directly focus on the DPT properties of disordered binary ferromagnetic alloy under the existence of a time dependent forcing magnetic field. From this point of view, in this work, by using the EFT with correlations based on the exact Van der Waerden identities, we intend to elucidate what is the impact of the amplitude and frequency of the oscillating magnetic field on magnetic phase transition properties of the disordered binary ferromagnetic alloy.

The remainder of the study is as follows: The dynamic equations off motions and dynamic order parameters (DOPs) of the kinetic disordered binary alloy model are described in Section 2. The numerical results and related discussions are given in Section 3, and finally Section 4 contains our conclusions.

2. Formulation

We consider a two dimensional disordered binary ferromagnetic alloy of the type $A_c B_{1-c}$ defined on a square lattice with a time dependent driving oscillating magnetic field. The lattice sites are randomly occupied by two different species of magnetic components A and B ($S_A = 1/2$ and $S_B = 1$) . Time dependent Hamiltonian describing our model is given by

$$\hat{H} = -J\sum_{\langle ij\rangle}[\delta_{iA}\delta_{jA} + \delta_{iB}\delta_{jB} + \delta_{iA}\delta_{jB} + \delta_{iB}\delta_{jA}]S_i S_j \xi_i \xi_j - \Delta\sum_i S_i^2 \delta_{iB}\xi_i - H(t)\sum_i(\delta_{iA} + \delta_{jB})S_i\xi_i, \quad (1)$$

where J is the ferromagnetic exchange interaction energies between type-i and type-j sites, the Δ is the single-ion anisotropy term, the S are classic Ising spin variables which can take values of $S = \pm 1$ for the A component and of $S = \pm 1, 0$ for the B component. ξ_i is a random variable that takes the value of unity or zero depending on the site i is occupied by a magnetic atom or not. It should be noted that performing the random configurational average denoted by $\langle\cdots\rangle_r$, the averaged value of ξ_i has a restriction $\langle\xi_{i=A}\rangle_r + \langle\xi_{i=B}\rangle_r = 1$, where $\langle\xi_{i=A}\rangle_r = c$ and $\langle\xi_{i=B}\rangle_r = 1 - c$ are the concentrations of the A and B atoms, respectively. Namely, based on this restriction, it is possible to say that there is no any unoccupied lattice site. The symbol $\delta_{i\alpha}$ ($\alpha = A$ or B) shows that a site i is occupied by a type-α ion. The first summation in Eq. (1) is over the nearest-neighbor site pairs while the second one is over all lattice sites. $H(t)$ denotes the time dependent oscillating magnetic field followed by

$$H(t) = h_0\cos(\omega t), \quad (2)$$

where t is time, h_0 and ω are amplitude and angular frequency of the driving magnetic field, respectively.

In order to study the dynamical evolution of the considered system, if we use a Glauber-type stochastic processes [45], the dynamic equations of motions can be obtained as follows:

$$\tau\frac{d}{dt}\langle\langle\xi_{i=A}S_{i=A}\rangle\rangle_r = -\langle\langle\xi_{i=A}S_{i=A}\rangle\rangle_r + \langle\langle\xi_{i=A}\tanh[\xi_{i=A}\beta(E_i + H(t))]\rangle\rangle_r,\ \tau\frac{d}{dt}\langle\langle\xi_{i=B}S_{i=B}\rangle\rangle_r = -\langle\langle\xi_{i=B}S_{i=B}\rangle\rangle_r + \left\langle\left\langle\xi_{i=B}\frac{2\sinh(\xi_{i=B}\beta(E_i + H(t)))}{2\cosh(\xi_{i=B}\beta(E_i + H(t))) + \exp(-\beta\Delta\xi_{i=B})}\right\rangle\right\rangle_r,\ \tau\frac{d}{dt}\langle\langle\xi_{i=B}S_{i=B}^2\rangle\rangle_r = -\langle\langle\xi_{i=B}S_{i=B}^2\rangle\rangle_r + \left\langle\left\langle\xi_{i=B}\frac{2\cosh(\xi_{i=B}\beta(E_i + H(t)))}{2\cosh(\xi_{i=B}\beta(E_i + H(t))) + \exp(-\beta\Delta\xi_{i=B})}\right\rangle\right\rangle_r, \quad (3)$$