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Investigation of oscillation frequency and disorder induced dynamic phase transitions in a quenched-bond diluted Ising ferromagnet

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ABSTRACT

Frequency evolutions of hysteresis loop area and hysteresis tools such as remanence and coercivity of a kinetic Ising model in the presence of quenched bond dilution are investigated in detail. The kinetic equation describing the time dependence of the magnetization is derived by means of effective-field theory with single-site correlations. It is found that the frequency dispersions of hysteresis loop area, remanence and coercivity strongly depend on the quenched bond randomness, as well as applied field amplitude and oscillation frequency. In addition, the shape of the hysteresis curves for a wide variety of Hamiltonian parameters is studied and some interesting behaviors are found. Finally, a comparison of our observations with those of the recently published studies is represented and it is shown that there exists a qualitatively good agreement.

1. Introduction

When a ferromagnetic material is subject to a time-dependent oscillating magnetic field, the system may not respond to the external magnetic field instantaneously, and this situation leads to some interesting phenomena. Namely dynamic phase transitions (DPTs) and dynamic hysteresis behavior originate due to a competition between time scales of the relaxation time of the system and oscillation period of the external magnetic field. On the other hand, at high temperatures and for the high amplitudes of the periodic magnetic field, the system is able to follow the external field with some delay while this is not the case for low temperatures and small magnetic field amplitudes. This spontaneous symmetry breaking indicates the presence of a DPT [1] which shows itself in the dynamic order parameter (DOP) which is defined as the time average of the magnetization over a full period of the oscillating field. According to early experimental studies, dating back to last century, there exists an empirical law for the hysteresis loop areal scaling [2]. Up to now, fairly well numerous theoretical studies have been dedicated to DPT and hysteresis properties of kinetic Ising models by using various methods such as Monte Carlo (MC) simulations [3–14], effective-field theory (EFT) [15,16], and mean-field theory (MFT) [4,5,17–19,25–29]. Apart from these, there exist a detailed geometrical description [30] and also an hysteresis criterion based on rate competition between the critical curvature and the potential-barrier height [31]. By employing standard Metropolis MC algorithm with periodic boundary conditions, the pure kinetic Ising model in a two-dimensional square lattice has been simulated by Lo and Pelcovits [3], and they found some evidences of a DPT. They also investigated the behavior of dynamic hysteresis for varying Hamiltonian parameters, however, they did not intend to make any classification for dynamic hysteresis behavior. Afterwards, by making use of MC simulations and MFT, Acharyya and Chakrabarti [4] have presented a comprehensive investigation of the pure kinetic Ising model and they showed that the hysteresis loops are asymmetric in the dynamically ordered phase while in a dynamic disordered phase, they are symmetric around the origin in a magnetization versus field amplitude plane. In Ref. [5], the attention has been focused on the behavior of dynamic hysteresis and dynamic loop area (DLA) of a pure kinetic Ising model by using both MFT and MC calculations. In addition, the frequency variations of the coercive field have been analyzed below the zero field critical temperatures. It has been concluded that the numerical results for the dynamic coercive field show a power law frequency variation for both cases. However, the coercive field calculated by MFT becomes frequency independent in the low frequency regime. Differences between the two methods (MFT and MC) have been explained by using a kind of Landau-type double well free energy mechanism. Moreover, there exist many previously published studies such as the domain wall motion and nucleation theory [21–24] regarding the hysteresis loop mechanism [20].

On the experimental picture, it can be said that a great many of experimental studies have been devoted to DPTs and hysteresis behaviors of Co films on a Cu (001) surface [32], [Co(4A°)/Pt(7A°)]

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multi-layer system with strong perpendicular anisotropy [33], thin polycrystalline $Ni_{80}Fe_{20}$ films [34], ultrathin ferromagnetic Fe/Au(001) films [35], epitaxial Fe/GaAs(001) thin films [36], epitaxial single ferromagnetic fcc NiFe(001), fcc Co(001), and fcc NiFe/Cu/Co(001) layers [37], $Fe_{0.42}Zn_{0.58}F_2$ [38], finemet thin films [39], and epitaxial Fe/GaAs(001) and Fe/InAs(001) ultrathin films [40]. After some detailed experimental investigations, it has been observed that experimental non-equilibrium dynamics of considered real magnetic systems strongly resemble the dynamic behavior predicted from theoretical calculations of a kinetic Ising model. It is clear from these works that there exists a strong evidence of qualitative consistency between theoretical and experimental studies.

Besides, the lattice models including impurities and defects have attracted considerable attention, because they are very useful to investigate the behavior of disordered systems in nature. For this purpose, more effective models have been introduced to examine the influences of disorder on the thermal and magnetic properties of real magnetic materials. For example, the effects of impurities on driving-rate-dependent energy loss in a ferromagnet under the time-dependent magnetic field have been analyzed by Zheng and Li [41] by using several well defined models within the frameworks of MFT and MC, and they found using MFT that the hysteresis loop area is a power law function of the linear driving rate as $A - A_0 \propto h^{\beta}$, where A_0, h and β are the static hysteresis loop area, the linear driving rate, and scaling exponent of the system, respectively. Very recently, the quenched site and bond diluted kinetic Ising models under the influence of a time-dependent oscillating magnetic field have been analyzed by making use of EFT [42,43] on a two-dimensional honeycomb lattice. In Ref. [42], the global phase diagrams including the re-entrant phase transitions are presented by the authors for site diluted kinetic Ising model, and they showed that the coexistence regions disappear for sufficiently weak dilution of lattice sites. Following the same methodology, the authors have concentrated on the influences of quenched bond dilution process on the dynamic behavior of the system. After some detailed analysis, it has been found that the impurities in a bond diluted kinetic Ising model give rise to a number of interesting and unusual phenomena such as re-entrant phenomena and the impurities to have a tendency to destruct the first-order transitions and the dynamic tricritical point [43]. Furthermore, it has also been shown that dynamically ordered phase regions get expanded with decreasing amplitude which is more evident at low frequencies.

Very recently, frequency dependencies of the dynamic phase boundary (DPB) and magnetic hysteresis of Ising model in an oscillating magnetic field have been examined by Punya et al. [19]. Based on MFT, they have represented the phase diagram in a magnetic field versus temperature plane for varying frequencies, in order to show the influence of the oscillation frequency of the external field on the hysteretic response of the system. According to their calculations, it has been found that the frequency dispersion of the DLA, the remanence and coercivity can be categorized into three distinct types for a fixed temperature. Although the detailed investigations and classifications of the hysteretic behaviors of pure kinetic Ising model have been done within the MFT [19], as far as we know, the dynamic hysteretic behavior within the EFT has not been studied for disordered kinetic Ising models. Main motivation of our study is to investigate the influences of the bond dilution process on the hysteretic response and dynamic phase diagrams in temperature versus applied field frequency plane of the system in the neighborhood of second-order phase transitions. In order to see the phase transition properties originating from quenched bond dilution, as well as applied field frequency, value of the magnetic field is designedly restricted in a special region ($h \in [0,1]$). From this point of view in this work, we intend to focus on the effects of the quenched bond dilution process on the dynamic hysteresis behavior of kinetic Ising model in the presence of a time-dependent oscillating external magnetic field by using the EFT with correlations based on the exact Van der Waerden identity for a spin-1/2 system. Present method is quite superior to MFT, since thermal fluctuations are partly considered in EFT. The outline of the paper can be summarized as follows. The dynamic equation of motion, DOP and DLA of the quenched bond diluted kinetic Ising model have been introduced in the next section. The numerical results and related discussions are given in Section 3, and finally Section 4 contains our conclusions.

2. Formulation

The kinetic Ising model is given by the time-dependent Hamiltonian

$$\mathcal{H} = -\sum_{\langle ij \rangle} J_{ij} S_i^z S_j^z - H(t) \sum_i S_i^z, \tag{1}$$

where the spin variables $S_i^z = \pm 1$ are defined on a honeycomb lattice ($q=3$) and the first sum in Eq. (1) is over the nearest-neighbor pairs of spins. We assume that the nearest-neighbor interactions are randomly diluted on the lattice according to the probability distribution function

$$P(J_{ij}) = p\delta(J_{ij} - J) + (1-p)\delta(J_{ij}), \tag{2}$$

where p denotes the concentration of active bonds. The term $H(t)$ in Eq. (1) is a time-dependent external magnetic field which is defined as

$$H(t) = h\cos(\omega t), \tag{3}$$

where h and $w = 2\pi f$ represent the amplitude and the angular frequency of the oscillating field, respectively. If the system evolves according to a Glauber-type stochastic process [44] at a rate of $1/\tau$ which represents the transitions per unit time then the dynamic equation of motion can be obtained as follows:

$$\tau \frac{d\langle S_i^z \rangle}{dt} = -\langle S_i^z \rangle + \left\langle \tanh\left[\frac{E_i + H(t)}{k_B T}\right]\right\rangle, \tag{4}$$

where $E_i = \sum_j J_{ij} S_j$ is the local field acting on the lattice site i, and k_B and T denote the Boltzmann constant and temperature, respectively. If we apply the differential operator technique [45,46] in Eq. (4) by taking into an account the random configurational averages we get

$$\frac{dm}{dt} = -m + \left\langle \left\langle \prod_{j=1}^{q=3} A_{ij} + S_j^z B_{ij} \right\rangle \right\rangle_r f(x)|_{x=0}, \tag{5}$$

where $A_{ij} = \cosh(J_{ij}\nabla)$, $B_{ij} = \sinh(J_{ij}\nabla)$, and $m = \langle\langle S_i^z \rangle\rangle_r$ represents the average magnetization. $\nabla = \partial/\partial x$ is a differential operator, and the inner $\langle \cdots \rangle$ and the outer $\langle \cdots \rangle_r$ brackets represent the thermal and configurational averages, respectively. When the right-hand side of Eq. (5) is expanded, the multispin correlation functions appear. The simplest approximation, and one of the most frequently adopted is to decouple these correlations according to

$$\langle\langle S_i^z S_j^z \ldots S_l^z \rangle\rangle_r \cong \langle\langle S_i^z \rangle\rangle_r \langle\langle S_j^z \rangle\rangle_r \cdots \langle\langle S_l^z \rangle\rangle_r \tag{6}$$

for $i \neq j \neq \cdots \neq l$ [47]. If we expand the right-hand side of Eq. (5) with the help of Eq. (6) then we obtain the following dynamic effective-field equation of motion for the magnetization of the quenched bond diluted kinetic Ising model:

$$\frac{dm}{dt} = -m + \sum_{i=0}^{q=3} \lambda_i m^i, \tag{7}$$