Minor loop analysis using Monte Carlo simulation for clusters with various magnetic site densities

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Abstract. Magnetic granular systems have been applied to many fields of study, e.g. spin glass properties or magnetic resistance phenomena. These magnetic granular systems have homogeneous densities of magnetic granules and there physical properties changes depending on its densities. In this study, to investigate magnetic properties of such granular systems, minor hysteresis loops analysis was performed using Monte Carlo simulation. As the granular systems, clusters with various magnetic site densities were prepared by simple diffusion model. Moreover, these clusters were analyzed from new point of view which is a concept of a “colony”. The results of minor loop analysis were considered associating with colony.

Keywords: magnetic hysteresis curve, Monte Carlo method, magnetic minor loop

1. Introduction

Magnetic granular systems have been studied for their physical interesting, i.e. spin glass properties or magnetic resistance phenomena and also for their engineering applications. Magnetic granular systems keep the homogeneous density of the magnetic granule in a non-magnetic matrix. Such magnetic granular systems changes its magnetic properties drastically depending on density of magnetic sites. These properties have been explained using statistical technique such as mean-field theory [1]. These techniques explain the magnetic properties well in strong magnetic fields, however, it would be insufficient to understand the magnetic properties in weak magnetic fields such as minor hysteresis loops because of the local magnetic structures which are not described in mean-field theory due to varieties of distance between nearest neighbor magnetic sites in granular systems. The major hysteresis loops are under more external magnetic field than that for saturation magnetization. On the other hand, minor hysteresis loops are under less external magnetic field than that for saturation magnetization. These minor
hysteresis loops are considered to have more information on magnetic properties than major hysteresis loops and some studies on minor loops analysis have been performed [2, 3].

In this paper, magnetic properties in weak magnetic fields are investigated for clusters with various magnetic site densities using Monte Carlo (MC) simulation for the minor loops analysis considering with varieties of distances between nearest neighbor magnetic sites.

2. Cluster construction and Numerical method

2.1. Cluster with various magnetic site density

Clusters which have various and homogenous magnetic site densities were prepared using simple diffusion model. In the model, a magnetic site transfer on lattice points in simple cubic lattice whose length of an edge is \( L \). The total number of lattice points is \( L^3 \). Namely, the diffusion area of magnetic sites is larger as the length of an edge \( L \) is larger. As an initial state, the magnetic sites fill all of the lattice points when \( L=22 \).

To disperse magnetic sites homogenously, diffusion attempt is repeated sufficiently. The diffusion progresses to exchange the state of a lattice point. A lattice point is chosen randomly and exchanges its state with another lattice point of nearest neighbor lattice points. It is also chosen randomly which nearest neighbor lattice point is chosen. This exchange attempt is repeated for other lattice point.

Figure 1 shows dispersion of magnetic sites for each density clusters. The length of a side was set as \( L=102, 60, 47, 41, 39, 35, 33 \). For instance, when \( L=33 \), the density of magnetic site is \( 100 \times \frac{22^3}{33^3} \approx 30\% \). When \( L=102, 60, 47, 41, 39, 35, 33 \), the density is nearly 1, 5, 10, 15, 20, 25, 30\%, respectively.

![Figure 1: Snapshot of magnetic site dispersion clusters.](image)

2.2. Monte Carlo method

Using clusters with various magnetic site densities above, the simulation is performed by Monte Carlo method. In this simulation, following Hamiltonian is set:
Each term of $H_J$, $H_D$ and $H_B$ represents exchange interaction energy, magnetic dipole interaction energy and applied magnetic field energy, respectively. Here $S_i$ denotes the magnetic moment of the magnetic site of $i$-th cell and $r_{ij}$ represents the vector between $i$-th site and $j$-th site. In the first term $H_J$, $J_{ij}$ stands for an exchange interaction energy constant for $i$-th and $j$-th sites. The exchange interaction works between nearest neighbor sites. In the second term $H_D$, $D$ stands for a magnetic dipole interaction constant. The magnetic dipole interaction works on all magnetic sites because it is due to magnetic field interspersed in all space. In the third term of $H_B$, $B$ represents applied magnetic field which acts equally all magnetic sites. The changing of $S_i$ on MC simulation progresses as spin-flips by Metropolis sampling. The random sampling is iterated sufficiently with acceptance probability $e^{-\Delta E/k_B T}$ at constant temperature $k_B T$. Here, $\Delta E$ is energy difference between the two state that calculated from $(1)$ [4, 5].

In this simulation, the parameters were set as $J_{ij}=1.0$, $D=0.01$ and $S_i$ was set as $|S_i|=1$. For details of MC method for magnetic dynamic process, see the references [6].

3. Results and Discussion

Figure 2 shows magnetic hysteresis curves. The thick line is major loop and thin lines are minor loops of each applied magnetic field $H_a$. Here, $H_a$ means maximum applied magnetic field for each minor loop.

Figures 3(a) and 3(b) show $H_a$ dependence of coercivity $H_c^*$ and hysteresis loss $W_f^*$ for minor loop. For the cluster of 30%, $H_c^*$ is reaching upper limit at larger magnetic field than other cluster. Similarly, $W_f^*$ is reaching upper limit at $H_a \approx 4.0 \times 10^{-2}$ for cluster with 10%, 15% and 20%, but that is increase at $H_a \approx 6.0 \times 10^{-2}$ and $8.0 \times 10^{-2}$ for 25% and 30% cluster. $\Delta H_c^*$ is defined as the difference of $H_c^*$ between small $H_a$ and large $H_a$. $\Delta W_f^*$ is also defined the same as $\Delta H_c^*$. Figure 4 shows dependence of $\Delta H_c^*$ and $\Delta W_f^*$ on magnetic site density. $\Delta H_c^*$ and $\Delta W_f^*$ are larger as the density is higher.
Figure 2: Major loop (thick line) and minor loops (thin lines) for the cluster whose magnetic site density is 30%.

Figure 3: Minor loop analysis for (a) magnetic coercivity $H_c^*$ and (b) hysteresis loss $W_F^*$.

Figure 4: Dependence of (a) $\Delta H_c^*$ and (b) $\Delta W_F^*$ on magnetic site density.

It is considered that the main factor of ferromagnetism is exchange interaction, hence, it seems to be benefit to regard clusters as a group of nearest neighbor sites which work exchange interaction. Here, we would like to introduce a concept of “colony”. Figure 5 shows image of “colony”. A “colony” is defined as a group of magnetic sites linked by the distance of first nearest neighbors in this paper.
Figures 6 (a) and (b) are the number of colony and magnetic sites plotted against colony size. Clusters of lower magnetic site densities tend to have much more colonies whose size is small than that of higher densities. Large size colonies tend to exist in high density cluster. Figure 7 is density dependence of size of the largest colony in each cluster. The size of the largest colony in 30% cluster is more than four times of the largest one in 25% cluster.

Clusters with high density have large size colonies. Magnetic moments of large size colonies hard to change a direction in weak magnetic fields $H_a$ due to the large coercivity, although one of small size colonies change same direction easily at weak magnetic fields $H_a$. Therefore, small size colonies are dominant for magnetic property of cluster under weak magnetic fields $H_a$. On the other hands, magnetic moments of large size colonies can change to direction at strong magnetic fields $H_a$. Thus, large size colonies are mainly contribute for $H_c^*$ at strong magnetic fields. $W_F^*$ depends $H_c^*$ due to large size colonies and the total magnetic moments adding small size colonies.

Figure 5: Schematic diagram for magnetic sites and colony.

Figure 6: Colony size dependence of (a) colony number and (b) magnetic site number.
Figure 7: Dependence of magnetic site density for maximum colony size.

4. Conclusion

The results of minor loops analysis show that $\Delta H_c^*$ and $\Delta W_F^*$ are larger for higher density magnetic cluster including large size colonies. Therefore, the colony size distribution in magnetic cluster could be estimated by $\Delta H_c^*$ and $\Delta W_F^*$. These analysis methods would be useful to know the more precise property of magnetic glandular systems.

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