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 loop analysis was performed using Monte Carlo simulation. As the granular systems, clusters with various magnetic site densities were constructed 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, although the each distance between nearest neighbour granules takes various values. Such magnetic granular systems changes its magnetic properties drastically, hence, it is important that the relations between the density and the magnetic properties are investigated considering the mechanism.

Magnetic hysteresis loop analysis is one of an effective analysis method to know the magnetic properties. The loop is obtained by measuring magnetization changing the external magnetic field. Ordinary, external magnetic field is applied up to when the magnetization is saturated. The loop which the magnetization is saturated is called as major loop. On the other hand, hysteresis loop under less external magnetic field than that for saturation magnetization is called as minor loop. These minor loops is considered to have more information on magnetic properties than major loop and minor loop analysis are performed other studies [1, 2]. In this study, using this minor loop analysis and Monte Carlo simulation, magnetic properties are investigated for clusters with various magnetic site densities.

2 Cluster construction and Numerical method

2.1 Cluster with various magnetic site density

Clusters which have various and homogenous magnetic site densities were constructed using simple diffusion model. In the model, a magnetic site transfer on lattice points in simple cubic lattice whose length of a side is L. The total number of lattice points is L^3. Namely, the diffusion area of magnetic sites is larger as the length of a side L is larger. As an initial state, the magnetic sites fill all of the lattice points when L=14.

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.

The length of a side was set as L=68, 40, 31, 27, 25, 23, 21. For instance, when L=21, the density of magnetic site is $100\text{x}15^3/22^3 \fallingdotseq 30\%$. When L=68, 40, 31, 27, 25, 23, 21, the density is nearly 1, 5, 10, 15, 20, 25, 30%, respectively.

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:

$$\begin{aligned} H &= H_J + H_D + H_B \\ &= -\sum_{near} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j \\ &\quad + D\sum_{all}\left(\frac{\mathbf{S}_i \cdot \mathbf{S}_j}{\left|\mathbf{r}_{ij}\right|^3} - \frac{3}{\left|\mathbf{r}_{ij}\right|^5}\left(\mathbf{S}_i \cdot \mathbf{r}_{ij}\right)\left(\mathbf{S}_j \cdot \mathbf{r}_{ij}\right) \right) \\ &\quad + B\sum_i \mathbf{S}_i . \end{aligned} \tag{1}$$

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 neighbour 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, ΔE is energy difference between the two state that calculated from eqn. (1) [3, 4].

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 [5].

3 Results and Discussion

Figure 1 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.

Figure 2(a) and 2(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 weaker magnetic field than other cluster. Similarly, W_F^* is reaching upper limit at $H_a \fallingdotseq 1.0\text{x}10^{-2}$ for cluster with 20%, but that is increase at $H_a \fallingdotseq 1.8\text{x}10^{-2}$ and $2.4\text{x}10^{-2}$ for 25% and 30% cluster. In another point of view, the gap of H_c^* and W_F^* between small H_a and large H_a are larger as the density is higher.

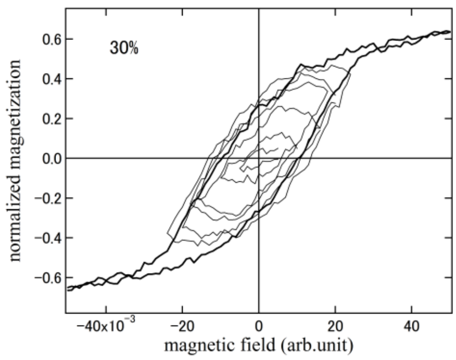

Fig. 1. Major loop (thick line) and minor loops (thin lines) for the cluster whose magnetic site density is 30%. .

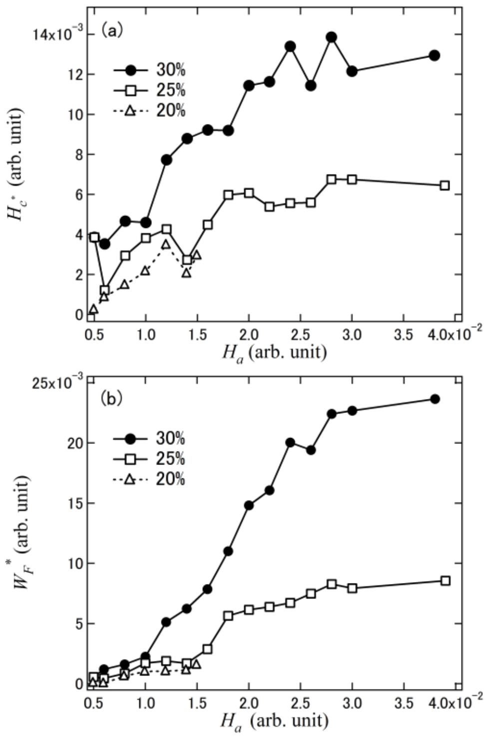

Fig. 2. Minor loop analysis for (a) magnetic coercivity H_c^* and (b) hysteresis loss W_F^*.

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 neighbour sites which work exchange interaction. Here, we would like to introduce a concept of "colony". A "colony" is defined as a group of magnetic sites linked by the distance of first nearest neighbors in this paper.

Figure 3 is number of colony plotted against colony size of magnetic site. Clusters of lower magnetic site densities tend to have much more colonies whose size is small than that of higher densities. Figure 4 is density dependence of size of the largest colony in each cluster. Large size colony tend to exist in high density cluster, especially, the size of the largest colony in 30% cluster is more than four times of the largest one in 25% cluster.

In clusters whose magnetic site densities, many colonies tend to be large size and have large magnetic energy, accordingly, many colonies could show low magnetization due to dull response in weak magnetic fields H_a. On the other hands, these colonies respond in strong magnetic fields H_a, therefore, the gap of H_c^* and W_F^* between small H_a and large H_a is considered to be larger in clusters with higher magnetic site densities.

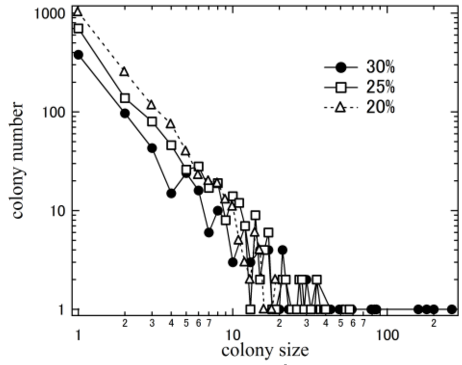

Fig. 3. Colony size distribution of each cluster with various magnetic site densities.

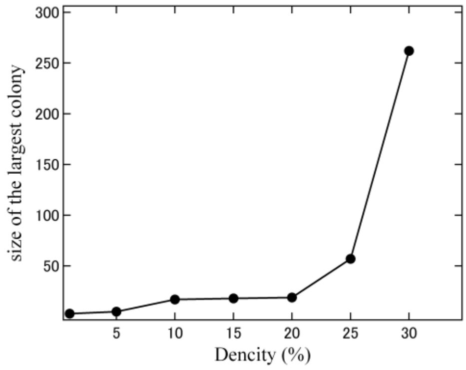

Fig. 4. Dependence of magnetic site density for maximum colony size. .

4 Conclusion

The magnetic properties for clusters with various magnetic site densities changes depending on its densities. The results of minor loop analysis are quit different for each density e.g., the gap of coercivity H_c^* and hysteresis loss W_F^* between small H_a and large H_a are larger as the density is higher. The differences are explained by colony size distribution. These analysis methods would produce some new point of view for the development of magnetic glandular systems.

References

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