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Control of structures of feeble magnetic particles by utilizing induced magnetic dipoles

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Abstract

Interactions among induced magnetic dipoles were observed in the systems of feeble magnetic substances that have been neglected so far. Furthermore, by applying this interaction to many particle systems, some peculiar alignments were obtained. These phenomena would be of use as a control of material structures, and bring new applications of magnetic fields in various processes.

Keywords: Feeble magnetic materials; High magnetic fields; Induced magnetic dipoles; Self-organization; Gold rods; Gold balls; Palladium rods

1. Introduction

Recently, effects of magnetic fields on para- and diamagnetic, namely, feeble magnetic substances, have attracted much attention, and various phenomena have been discovered such as magnetic levitations [1,2], Moses effect [3], and so on. These effects are mainly on magnetic forces, and magnetic forces can be expressed as interactions between feeble magnetic substances and gradient fields. Conversely, interactions among feeble magnetic substances under magnetic fields have been neglected so far. In ferromagnetic substances, interactions through their magnetic dipoles can be observed clearly [4,5], and the energy of the interactions of two magnetic dipoles is expressed as

$$U = \frac{\mu_0}{4\pi}\left\{\frac{\boldsymbol{m}_a \cdot \boldsymbol{m}_b}{r^3} - \frac{3(\boldsymbol{m}_a \cdot \boldsymbol{r})(\boldsymbol{m}_b \cdot \boldsymbol{r})}{r^5}\right\}[\mathrm{J}], \tag{1}$$

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where μ_0 is the permeability of vacuum, $\boldsymbol{m}_\mathrm{a}$ and $\boldsymbol{m}_\mathrm{b}$ are the magnetic dipoles, and $\boldsymbol{r}$ and r are the vector between two dipoles and its distance, respectively. On the other hand, for feeble magnetic substances, magnetic dipoles are induced only under magnetic fields, and their values are extremely small. Therefore, the energy of the interactions is too small, and it is not observed usually. However, through elaborate experiments using high magnetic fields of several teslas, we confirmed that such interactions can be observed visually even in feeble magnetic substances. It was then expected that alignments or structures of feeble magnetic substances could be controlled utilizing the interactions. Here, we report the observations of the induced magnetic dipole interactions and basic researches on the control of structures of feeble magnetic substances and discuss the importance of applied magnetic field distribution to attain this.

2. Induced dipole interactions between two samples

First, we observed induced magnetic dipole interaction between two objects. To apply magnetic fields, we used a cryo-cooler-cooled superconducting magnet with a 100 mm diameter room-temperature bore. In this study, the magnet was placed vertically and the field direction was parallel to that of gravity. Palladium (paramagnetic, volume magnetic susceptibility $\chi = 7.78 \times 10^{-4}$ [in SI units]) and gold (diamagnetic, $\chi = -3.45 \times 10^{-5}$ [in SI units]) rods were used as samples. Both rods were 1.0 mm in diameter and 5.0 mm in height. Sample rods were held side by side, with some spacing (~1.0 mm), by polyester fibers in the bore of the magnet. The area where magnetic fields were almost homogeneous in the horizontal direction, 149 mm above the field center along bore axis (z-axis), was selected as the samples' position in order to avoid horizontal magnetic force effects. Experiments were performed in three pairs of the samples such as palladium–palladium, palladium–gold, and gold–gold. From this configuration, the magnetic field was increased gradually and the distance between samples was observed. Fig. 1 shows the result for the palladium–palladium pair. The upper figure shows the initial state, and the lower shows the state with a 6 T magnetic field. From this result, we see that the distance between samples was increased by about 0.4 mm by the application of a 6 T magnetic field. This could be because the samples repelled each other through induced magnetic dipoles. However, no significant interaction was observed in the case of the palladium–gold and gold–gold pairs. This seems to be because the absolute value of the volume magnetic susceptibility of gold is only 10^{-1} as large as that of palladium and the magnetic dipoles induced in the gold samples were too small. Quantitative analysis was then performed on the result of the palladium–palladium pair. From the experimental result, the forces derived from the dipole

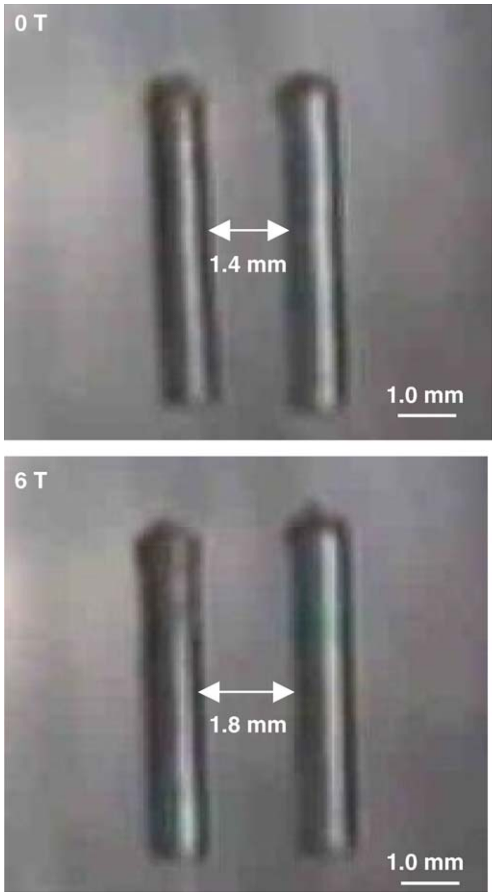

Fig. 1. Observation of repulsive interaction of palladium rods under a 6 T magnetic field.

interaction were estimated to be 8.5×10^{-7} N. However, this value of the force can also be calculated. The magnetic field around the samples was spatially distorted due to the induced magnetic dipoles, and the distribution was calculated by computer. From the result, the value of magnetic forces acting in the horizontal direction was found to be 2.4×10^{-7} N. The experimental result and the calculated value were in substantial agreement. From these results, we see that magnetic dipole interactions can be observed even in feeble magnetic substances by controlling experimental conditions carefully.

Then, we confirmed that such interactions can be enhanced by considering the effect of surroundings. In the above experiment, existence of the environmental surroundings was neglected. By considering the environmental surroundings, Eq. (1) can be modified as follows:

$$U = \frac{\mu_0}{4\pi}\left\{\frac{\Delta \boldsymbol{m}_a \cdot \Delta \boldsymbol{m}_b}{r^3} - \frac{3(\Delta \boldsymbol{m}_a \cdot \boldsymbol{r})(\Delta \boldsymbol{m}_b \cdot \boldsymbol{r})}{r^5}\right\}[\mathrm{J}], \quad (2)$$

where $\Delta \boldsymbol{m}$ represents the differences of magnetic dipoles between samples and surroundings. According to this equation, the energy of interactions can be enlarged by selecting environmental surroundings properly, and then the interactions can be enhanced. This means that magneto-Archimedes effect, enhancement of magnetic forces due to the effect of environmental surroundings [2], also appears in magnetic dipole interactions. This magneto-Archimedes effect was examined experimentally in the gold–gold pair. In the experiment, to enhance the effect, manganese dichloride aqueous solution was selected as paramagnetic media. The concentration of used solution was 40 wt%, and its susceptibility 7.99×10^{-4} (in SI units). By using this solution as surrounding medium, the same procedure as above was performed. The result is shown in Fig. 2. The upper figure shows the initial state, and the lower shows the state with a 3 T magnetic field. Due to the existence of the surrounding medium, $MnCl_2$ aqueous solution, the interaction was enhanced and the distance between samples was increased by about 0.3 mm. Therefore, it was confirmed that the induced magnetic dipole interactions can be enhanced by selecting proper environmental surroundings, i.e., by considering the magneto-Archimedes effect.

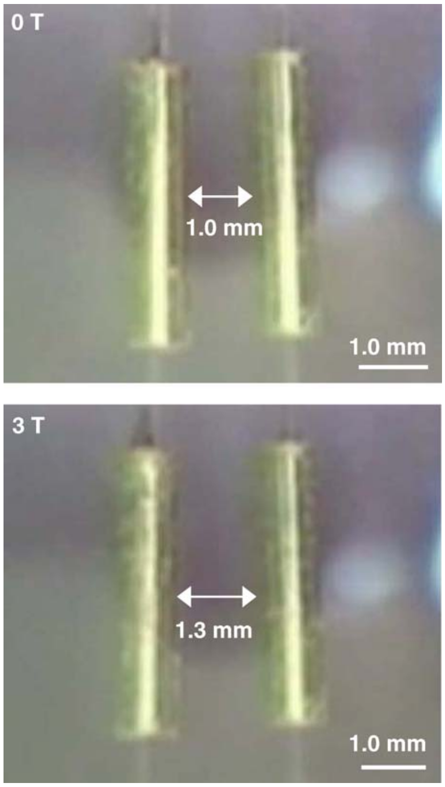

Fig. 2. Observation of enhancement of repulsive interaction of gold rods by magneto-Archimedes effect of surrounding medium.

3. Alignments of feeble magnetic particles utilizing induced magnetic dipole interactions

Subsequently, experiments were done using many feeble magnetic particles. It is known that magnetic dipole interactions lead dispersed particles to some ordered alignments. However, only systems containing ferromagnetic substances have been considered so far, and such applications have been restricted to a few materials. The applications of this effect to systems of feeble magnetic substances would make it possible to control structures of various materials, which would be useful in material processing. Therefore, experiments to examine such possible applications were performed.

First, alignments parallel to magnetic fields were observed. The sample particles used in this experiment were glass beads (~0.8 mmϕ), which are diamagnetic and have volume magnetic susceptibility of -1.8×10^{-5} (in SI units). Manganese dichloride aqueous solution of 40 wt% was used as a medium in consideration of magneto-Archimedes effect. In these experiments, the same magnet used previously was set horizontally. The glass beads and $MnCl_2$ aqueous solution were put in a glass cell, which was inserted into the bore of the magnet. One of the cell edges was fixed at the center of the field, and the glass beads were initially gathered at that side. From this configuration, magnetic fields were increased gradually. Then, magnetic forces acted on the glass beads, and they moved to the other side of the cell to avoid the higher field region. These processes were observed from the bottom of the cell with a CCD camera. The result of these experiments is shown in Fig. 3. In this figure, the magnetic field was applied parallel to the space, decreasing from right to left, and its intensity was 2.5 T. As seen in this figure, the glass beads aligned in chain-like formations, parallel to the applied field, as they moved away from the center of the fields. These formations were derived from the attractive interactions among magnetic dipoles induced in the glass beads.

Alignments perpendicular to fields were then observed. In this experiment, the magnet was placed vertically and a petri dish, containing the sample particles and surrounding medium, was placed in its bore. The sample particles used in this case were gold balls 1.0 mm in diameter; 40 wt% $MnCl_2$ aqueous solution was used as the surrounding medium. The gold balls were positioned 149 mm above the field center, where magnetic fields were only slightly larger (~0.2%) at the wall side than at the middle of the bore. From this configuration, magnetic field was applied and the two-dimensional alignments of the balls observed from above. To clearly observe the forces derived from dipole interactions in the horizontal direction, the magnetic field intensity was adjusted and the apparent weights of the gold balls were set to zero utilizing vertical magnetic forces. That is, magneto-Archimedes levitation was applied [2]. Fig. 4 shows the magneto-Archimedes levitation state of gold balls observed from above. During levitation, the gold balls gathered to the middle of the bore, influenced by slight radial magnetic forces. However, the gathering balls were not closely packed and formed triangle-lattice alignments with some spacing. This formation of the lattices was caused by the repulsive interactions among each magnetic dipole induced in the gold balls. Alignments perpendicular to fields can be controlled by repulsive interactions among induced magnetic dipoles.

Fig. 3. Chain-like alignments of glass beads in 40 wt% $MnCl_2$aq. The magnetic field was directed from left to right, and its intensity was 2.5 T at the field center.

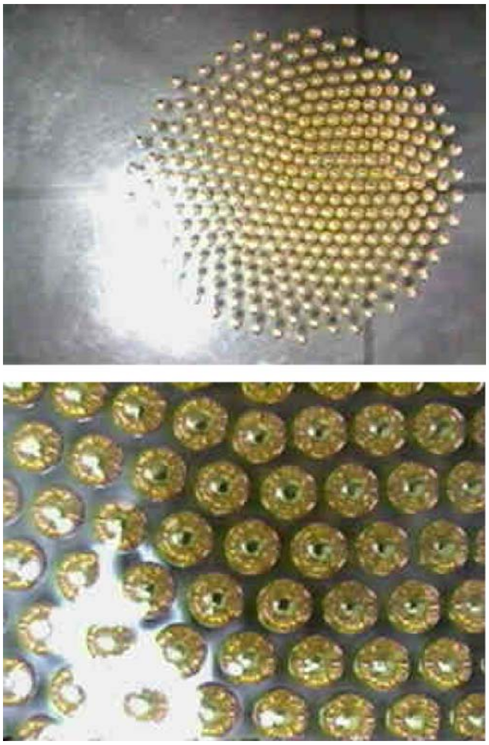

Fig. 4. Triangle-lattice alignments of gold balls in 40 wt% $MnCl_2$aq. The direction of magnetic field was perpendicular to this space, and its intensity was 4.9 T. The lower figure is a close-up view of the upper one.

Finally, we would like to mention about the importance of magnetic field homogeneity in sample plane to obtain a two-dimensional structure. Even though feeble magnetic particles are introduced under high magnetic fields, formation of alignment with some spacing by induced magnetic dipoles interaction cannot be observed if the homogeneity of the applied magnetic field in the sample plane is not good enough. To confirm this, we carried out series of experiments that observe two-dimensional structures by applying the same magnetic field in the center with changing magnetic field homogeneity. Fig. 5 shows the results of this series of experiments. The particles used here were gold with 1 mm diameter and the medium was $MnCl_2$ aqueous solution (40 wt%). Applied magnetic field in the center was always 5 T. In case of Fig. 5(a), the sample position was fixed at 143 mm above the field center, where difference of magnetic fields between center of the bore ($r = 0$) and 3 mm apart from the center in radial direction ($r = 3$) was 4.0×10^{-4} T. The fixed position along the bore axis and difference of magnetic fields between $r = 0$ and 3 in case of Figs. 5(b), (c) and (d) were 145 mm, 3.0×10^{-4} T, 147 mm, 2.3×10^{-4} T, and 149 mm, 1.3×10^{-4} T, respectively. As seen in Fig. 5, spacing between particles due to the repulsive interaction by induced magnetic dipoles change apparently depended on the slight difference of the magnetic fields homogeneity in the sample plane. To obtain a well aligned structure, one needs to apply relatively uniform magnetic fields.

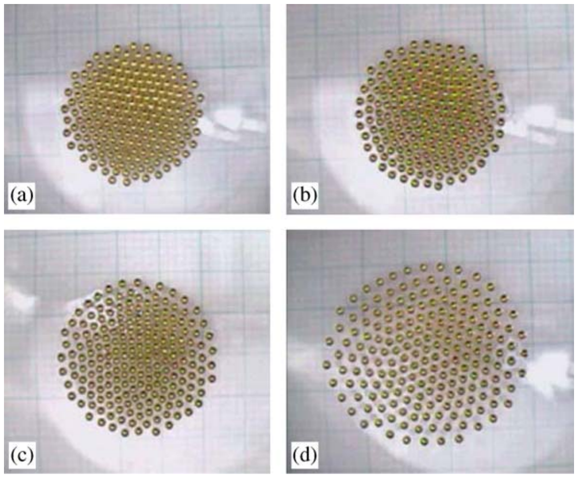

Fig. 5. Effect of radial magnetic field homogeneity on the structure of particles. Applied magnetic field at the center of this sample plane was always 5 T. The distance between magnetic field center and sample plane, and the difference of magnetic field between center of the sample plane and 3 mm from the center in radial direction were (a) 143 mm, 4.0×10^{-4} T, (b) 145 mm, 3.0×10^{-4} T, (c) 147 mm, 2.3×10^{-4} T, and (d) 149 mm, 1.3×10^{-4} T, respectively.

4. Conclusions

In this study, interactions among magnetic dipoles induced in feeble magnetic substances were observed. Then, we confirmed that this interaction could be enhanced by considering magneto-Archimedes effect. Furthermore, by applying this interaction to many particle systems, some ordered structures such as chain-like alignments and triangle-lattice alignments were obtained. Such a formation of ordered alignment was known in systems that contain ferromagnetic materials, so far. As confirmed here, it was found that the formation of alignment was attained even if the systems consisted of only feeble magnetic materials. Because magnetism is the property that all materials have, the conclusion drawn here is that control of structures or self-organization will be possible in the wide range of materials. Therefore, these phenomena suggest new applications of magnetic fields to various fields such as material processing.

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