Transactions of the Materials Research Society of Japan 28 [2] 231-233 (2003)

Control of Alignments of Feeble Magnetic Particles Utilizing Induced Magnetic Dipole Interactions

T. Takayama*, Y. Ikezoe*, H. Uetake*, N. Hirota*,**, and K. Kitazawa*,**
*University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8651
Fax: 81-4-7136-3767, e-mail: kk16122@mail.ecc.u-tokyo.ac.jp
**Japan Science and Technology Corp., 4-1-8 Honcho, Kawaguchi, Saitama 332-0012
Fax: 81-48-226-5651, e-mail: kitazawa@jst.go.jp

The ordered alignments of feeble magnetic particles were obtained utilizing induced magnetic dipole interactions. Recently, interactions between feeble magnetic substances and gradient fields, namely, magnetic forces, have been drawing attention. On the other hand, interactions between these substances under magnetic fields have been neglected because they induce extremely small dipoles. However, through elaborate experiments with high magnetic fields of several teslas, we confirmed that interactions of induced magnetic dipoles can be observed even in feeble magnetic substances. Utilizing these interactions, feeble magnetic particles create ordered structures such as chain-like or triangle-lattice-like alignments. These results indicate that structures of feeble magnetic substances can be controlled by magnetic fields, which could be useful in material processing and other fields.
Key words: magnetic dipole interaction, feeble magnetic substance, high magnetic field, chain-like alignment, triangle-lattice-like alignment

1. INTRODUCTION

Recently, magnetic forces have been drawing attention as the effect of magnetic fields on para- and diamagnetic substances, namely, feeble magnetic substances. Magnetic force is in proportion to magnetic susceptibility and to products of a magnetic field and its gradient. In feeble magnetic substances, the effects of magnetic forces are usually trivial because their magnetic susceptibility value is only $10^{-4\sim-6}$. However, these effects can be observed even in feeble magnetic substances under high magnetic fields of several teslas (and the product of the field and its gradient is over several hundred T^2/m), and they cause various interesting phenomena[1)-3)]. The effects of magnetic forces can be expressed as interactions between feeble magnetic substances and gradient fields. On the other hand, interactions among feeble magnetic substances under magnetic fields have been neglected so far. In ferromagnetic substances, interactions through magnetic dipoles can be observed clearly[4),5)], and the energy of the interaction of two magnetic dipoles is expressed as

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

where μ_0 is the permeability of the vacuum, $\boldsymbol{m}_a$ and $\boldsymbol{m}_b$ are the magnetic dipoles, and $\boldsymbol{r}$ and r are the vector between two dipoles and its absolute value, respectively. In regard to feeble magnetic substances, magnetic dipoles are induced only under magnetic fields, and their values are extremely small. Therefore, the interaction energy is very low, and interactions are not usually observed. However, through elaborate experiments with high magnetic fields of several teslas, we confirmed that interactions among feeble magnetic substances can be observed under proper conditions[6)]. Furthermore, such interactions can be enhanced when their environmental surroundings are selected properly. From these results, it is expected that alignments or structures of feeble magnetic substances are controlled by the interactions and that such control can have various applications. This paper reports basic research on the control of alignments of feeble magnetic substances.

2. ALIGNMENTS OF FEEBLE MAGNETIC PARTICLES

Induced magnetic dipole interactions have been observed in many feeble magnetic particles. It has been known that magnetic dipole interactions lead dispersed particles to ordered alignments[4),5)]. However, only systems containing ferromagnetic substances have been studied so far, and applications have been restricted to a few substances. The application to systems of feeble magnetic substances would make it possible to control

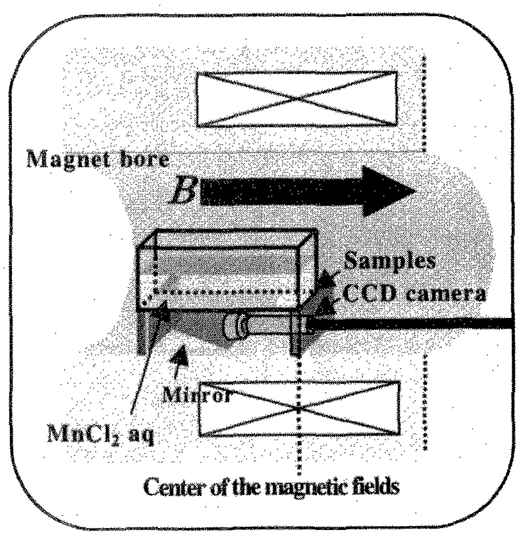

Fig. 1 Experimental set-up for observation of the alignments parallel to magnetic fields.

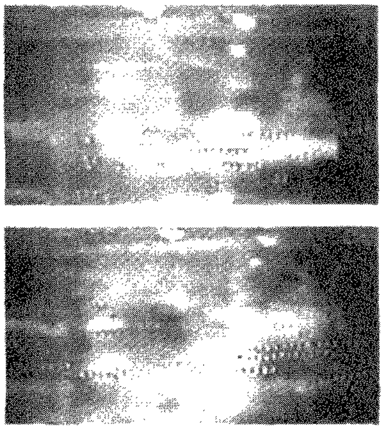

Fig. 2 Chain-like alignments of glass beads in $MnCl_2$aq. The concentration of $MnCl_2$aq was 30 wt% in the upper figure, and that was 40 wt% in the lower one, and the intensity of magnetic fields was 2.5 T in each figure.

structures of various substances, which would be useful in industrial fields. Therefore, experiments to observe the changes of alignment feeble magnetic particles under applied magnetic fields were carried out to examine possible applications. In the experiments, alignment parallel and perpendicular to magnetic fields were observed.

2.1 CHAIN-LIKE ALIGNMENTS

First, alignments parallel to magnetic fields were observed. The experimental set-up for this case is shown in Fig. 1. The samples used in this experiments were glass beads (~ϕ0.8 mm) which were diamagnetic and had a volume magnetic susceptibility of -1.8×10^{-5}[in SI units]. Manganese dichloride aqueous solution ($MnCl_2$aq) was selected as the medium in which the samples were dispersed in consideration of the enhancement of magnetic dipole interactions (magneto-Archimedes effect)[6]. In the experiments, a superconducting magnet with a room temperature bore of 100 mmϕ was placed horizontally. A glass cell in which the samples and $MnCl_2$aq were placed was inserted into the bore of the magnet. One of the cell edges was fixed at the center of the magnetic fields, and the samples were gathered at the edge of the cell under the initial conditions. From this configuration, the magnetic fields were increased gradually. Then the samples were moved towards the other edge of the cell by the magnetic forces due to the external magnetic fields. These processes were observed from the bottom of the cell with a CCD camera. The results are shown in Fig. 2. The direction of applied magnetic fields was from the left to the right in these figures. The concentration of $MnCl_2$aq in the upper figure was 30 wt%, and that in the lower one was 40 wt%. The magnetic susceptibilities of each solution were 5.53×10^{-4}[in SI units] and 7.99×10^{-4}[in SI units], respectively. The intensity of the magnetic fields was 2.5 T at the right side of the figure, that is, at the center of the magnetic fields in each case. These results show that the particles formed chain-like alignments parallel to the directions of the magnetic fields because of attractive interactions among induced magnetic dipole interactions. Furthermore, longer chains were observed when the concentration of $MnCl_2$aq was larger, that is, the paramagnetic susceptibility of the surroundings became larger because apparent magnetic dipoles induced in the samples became larger and their interactions were enhanced.

2.2 TRIANGLE-LATTICE-LIKE ALIGNMENTS

Next, alignments perpendicular to magnetic fields were observed. The experimental set-up for this case is shown in Fig. 3. The samples were gold balls (volume magnetic susceptibility χ = -3.45×10^{-5}[in SI units], density ρ = 19.32×10^{3}[kg/m^3]) or alumina balls (χ = -1.81×10^{-5}[in SI units], ρ = 3.97×10^{3}[kg/m^3]). Both balls were 1.0 mm in diameter. The medium use in this case was 40 wt% $MnCl_2$aq. In this experiment, the magnet was placed vertically, and a glass petri dish was placed in its bore. The samples and $MnCl_2$aq were put in the petri dish. The plane where the samples were dispersed was placed 149 mm above the center of the magnetic fields. The intensities of the magnetic fields in this vertical position were slightly larger (~0.2%) at the wall than in the middle. When magnetic fields are applied in this configuration, magnetic forces act on the samples and $MnCl_2$aq vertically, and the samples apparently become lighter. To observe effectively the forces in a horizontal direction due to induced magnetic dipole interaction, the intensities of magnetic fields were adjusted and the apparent weights of the samples were set at zero. That is, magneto-Archimedes levitation states were used[3]. In the levitation states, the dispersed samples gathered in the middle because of the slight radial magnetic forces. Figure 4 and 5 show these state observed from above. Figure 4 shows the case of the gold balls, and Fig. 5 shows that of the alumina balls. The direction of the magnetic fields was perpendicular to this space, and their intensities were 4.9 T in Fig. 4 and 1.6 T in Fig. 5. These results show that the samples

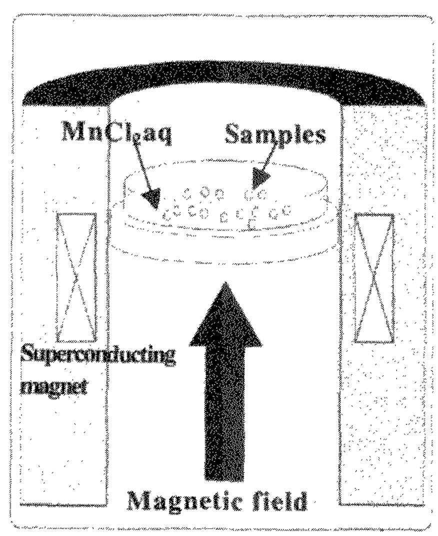

Fig. 3 Experimental set-up for observation of the alignments perpendicular to magnetic fields.

gathering to the middle were not packed completely but formed triangle-lattice-like alignments at some intervals. These formations of the lattices seem to be caused by repulsive interactions among each magnetic dipole induced in the samples. In these results, there were some disorders in the lattices, which seemed to be derived from the inhomogeneities of the distributions of the magnetic fields in the radial directions and from the nonuniformities of the particle size. Therefore, improvements in the experimental conditions would lead to more orderly lattice structures. These results show that the formation of ordered structures can be obtained not only in systems containing ferromagnetic substances but also in system of feeble magnetic substances by controlling experimental conditions properly.

3. SUMMARY

In this study, possible control of the alignment of feeble magnetic particles by magnetic fields was studied. Recently, our research confirmed that even in feeble magnetic substances magnetic dipole interaction can be observed. Though the interactions are small, well-arranged experimental conditions enable feeble magnetic particles to form some ordered structures; chain-like alignments parallel to and triangle-lattice-like alignments perpendicular to the magnetic fields. These results show that alignments or structures can be controlled by magnetic fields even in feeble magnetic substances. These phenomena suggest new application of magnetic fields to various fields such as the fabrications of photonic crystals, the control of structures of composite materials and so on.

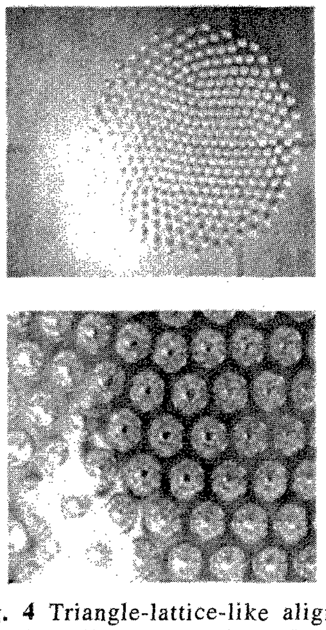

Fig. 4 Triangle-lattice-like alignments of gold balls in 40 wt% $MnCl_2$aq. The direction of magnetic field is perpendicular to this space, and its intensity is 4.9 T. The lower figure is a close-up view of the upper one.

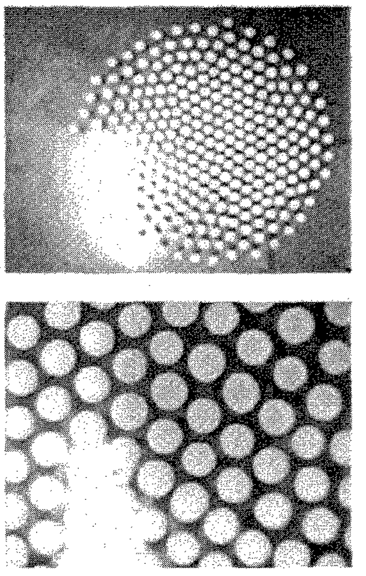

Fig. 5 Triangle-lattice-like alignments of alumina balls in 40 wt% $MnCl_2$aq. The direction of magnetic field is perpendicular to this space, and its intensity is 1.6 T. The lower figure is a close-up view of the upper one.

REFERENCES

1) N. Hirota, T. Homma, H. Sugawara, K. Kitazawa, M. Iwasaka, S. Ueno, H. Yokoi, Y. Kakudate, S. Fujiwara, and K. Kawamura : *Jpn. J. Appl. Phys.* **34** L991 (1996)
2) E. Beaugnon and R. Touriner : *Nature* **349** 470 (1991)
3) Y. Ikezoe, N. Hirota, J. Nakagawa, and K. Kitazawa : *Nature* **393** 749 (1998)
4) P. G. de Gennes and P. A. Pincus : *Phs. Kondens. Materie* **11** 189-198 (1970)
5) A. T. Skjeltorp : *Phys. Rev. Lett.* **51(25)** 2306-2309 (1983)
6) T. Takayama, Y. Ikezoe, T. Kaihatsu, H. Uetake, N. Hirota, and K. Kitazawa : *Trans. Mater. Res. Soc. Jpn* **27[1]** 43-46 (2002)

(Received December 21, 2002; Accepted March 30, 2003)