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Reduction of Field-Intensity to Achieve Magnetic Alignment of Non-Ferromagnetic Micron-Sized Particles by Reduction of Temperature

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The magnetic-alignment of micron-sized non-ferromagnetic crystals was measured in the temperature range of T=340K and 110K, using liquid ethanol or He gas as dispersing medium. The field intensity to achieve magnetic alignment can be reduced considerably due to the decrease of thermal agitation energy that randomizes the direction of crystal-axis. The field intensity of alignment is reduced even more, when certain amount of paramagnetic impurity ions is contained in the crystals. A number of attempts have begun recently to apply magnetic-alignment process to various types of material producing. It may increase the practicability of such attempts to realize grain-alignment with weak field-intensity produced at low temperature.
Key words: magnetic alignment at weak field, magnetic anisotropy, inorganic nonmetal, grains dispersed in gas, magnetic alignment at low temperature

1. INTRODUCTION

Magnetically stable-axes of micron-sized nonmetallic-crystals dispersed in fluid medium may align parallel to magnetic field at infinite field-intensity[1,2]. The alignment proceeds by the field-induced anisotropy energy originated from the anisotropy of magnetic susceptibility $\Delta\chi$ of the material. The field-intensity to achieve alignment is expected to decrease by the reduction of temperature T. This is because the energy of rotational Brownian motion that randomizes the direction of magnetic stable-axis decreases with the temperature of suspension sample.

The $\Delta\chi$ value of a non-ferromagnetic insulator is the sum of the intrinsic diamagnetic anisotropy $(\Delta\chi)_{DIA}$ and the paramagnetic anisotropy $(\Delta\chi)_{PARA}$ originating from the impurity ions. The amount of $(\Delta\chi)_{PARA}$ is known to be proportional to the reciprocal of T; reduction of temperature may lower the field of grain-alignment when concentration of paramagnetic ions is not negligible.

Temperature dependence of the magnetic grain-alignment process is examined in the range of T=340K and T=170K for paramagnetic and diamagnetic nonmetallic-crystals using liquid ethanol as dispersing medium. Preliminary results of the magnetic-alignment performed for diamagnetic graphite-crystals dispersed in cold He gas is reported, which is a step to realize non-ferromagnetic grain alignment at a practical weak field.

2. EFFECT OF TEMPERATURE ON MAGNETIC-ALIGNMENT

Variation of the degree of grain-alignment, due to increase of field-intensity B, observed for micron-sized diamagnetic particles was often analyzed successfully by the Langevin theory[3]. Degree of alignment is generally defined by an order parameter, which is a Boltzmann average at temperature T described as

$$\langle m\rangle = \langle (3\cos^2\theta - 1)/2\rangle. \qquad (1)$$

Angle between a magnetically stable axis and field direction is denoted as θ. The Boltzmann average is calculated by using the free energy U of a particle,

$$U = -(NB^2/2)\{\chi_\perp + \Delta\chi\cos^2\theta\}. \qquad (2)$$

$\Delta\chi$ is defined as $\Delta\chi = \chi_\parallel - \chi_\perp$ where $\chi_\parallel$ and $\chi_\perp$ are the molar susceptibilities parallel and perpendicular to the stable axis, respectively. The mol number of the molecules composing the particle is denoted as N.

The experimental $\langle m\rangle$-B relationship was obtained from the light intensity $I(B_i)$ transmitted through sample suspension at field intensity B_i. The experimental variations of light intensity and field intensity are shown as Fig.1. Field intensity was increased stepwise until $\Delta I_i = I_i - I_0$ reached a constant value ΔI_s, where almost all grains were aligned. The $\langle m\rangle$ value is obtained from the relation $\langle m\rangle = \Delta I_i / \Delta I_s$.

The field intensity, where $\langle m\rangle$ amounts to $\langle m\rangle = 0.8$, is defined as the field of full orientation B_s(see Fig.2), which is effective in describing the field intensity required to achieve alignment quantitatively[4,5],

$$B_s = (15k_B T / N\Delta\chi)^{1/2}. \qquad (3)$$

The value of B_s depends on N, $\Delta\chi$ and T, with $\Delta\chi = (\Delta\chi)_{DIA} + (\Delta\chi)_{PARA}$.

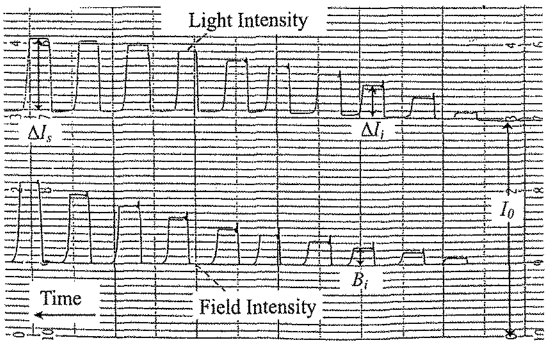

Fig.1 An example of chart sheet about light and field intensity observing grain alignment

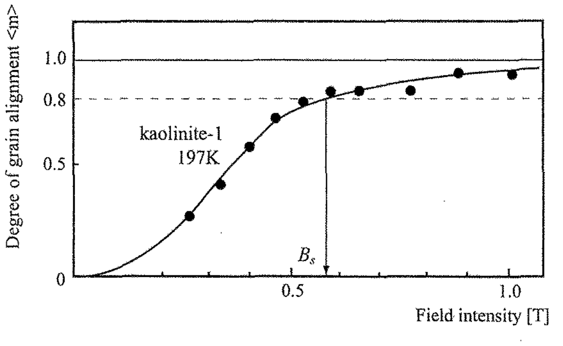

Fig.2 Relation between field intensity and the degree of grain alignment <m> for micro-crystal kaoline

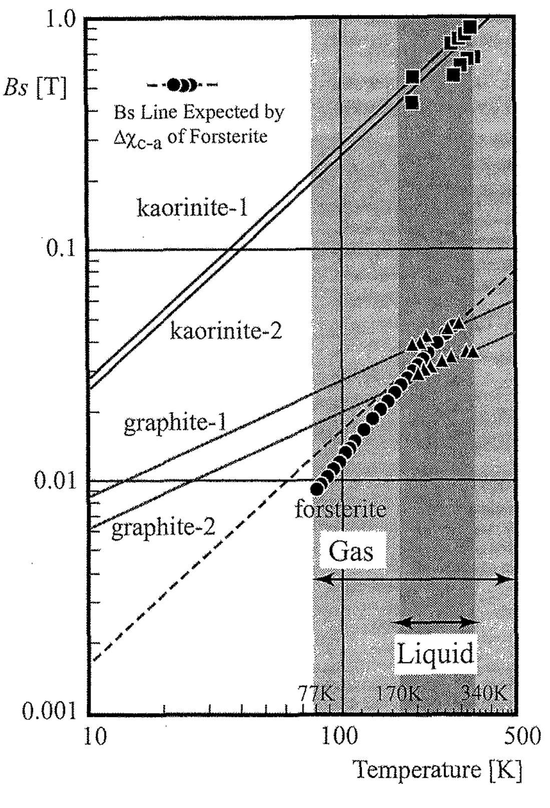

Fig.3 Temperature dependence of the magnetic-alignment process observed for micron-sized grains

3. OBSERVATIONS

The obtained B_s-T relationship for grains dispersed in liquid ethanol is shown in Fig.3. The measured data of graphite-1 and graphite-2 are shown in triangles. B_s is proportional to $T^{1/2}$ as expected from eq.(1). The effect of the Brownian thermal rotation assumed in the Langevin theory is confirmed by altering the temperature of the suspension[6].

B_s-T relation was measured for micron-sized kaolinite containing paramagnetic impurity ions[7]. Squares show the measured results of kaolinite-1 and kaolinite-2. Kaolinite is a classical ceramic material, which is difficult to synthesize. The reduction rate of Bs values with respect to T is considerably large compared to those observed for diamagnetic graphite; B_s is nearly proportional to T. This relationship is deduced from eq.(3), when $(\Delta\chi)_{PARA}$ is large enough compared to $(\Delta\chi)_{DIA}$; $\Delta\chi$ becomes proportional to $1/T$ [7].

B_s-T relationship for forsterite(Mg,Fe) is not measured but evaluated by the magnetic anisotropy between the a-axis and the c-axis $\Delta\chi_{c-a}$. The reduction rate is larger than kaolinite containing paramagnetic impurities. This is probably because weiss temperature is not negligible in the low-temperature region.

4. MAGNETIC ALIGNMENT OF GRAINS DESPERSED IN GAS MEDIUM

The temperature should be decreased below the melting point of ethanol in order to realize magnetic alignment at lower field intensity. One of the methods to reduce sample-suspension temperature is to disperse the grains in He gas and reduce the temperature of the gas suspension. Magnetic-alignment of graphite-grains dispersed in He gas was realized at room temperature[8,9] by a newly developed apparatus for this purpose (see Fig.4). Cold N_2 gas flows through a coiled copper pipe attached into a Dewar, which contained the suspension sample. Temperature of the sample suspension is controlled by the flow rate of the cold gas. Temperature dependence of magnetic alignment in the range of T=300K to 111K was observed for single-crystal grains of diamagnetic graphite grains using this system[10].

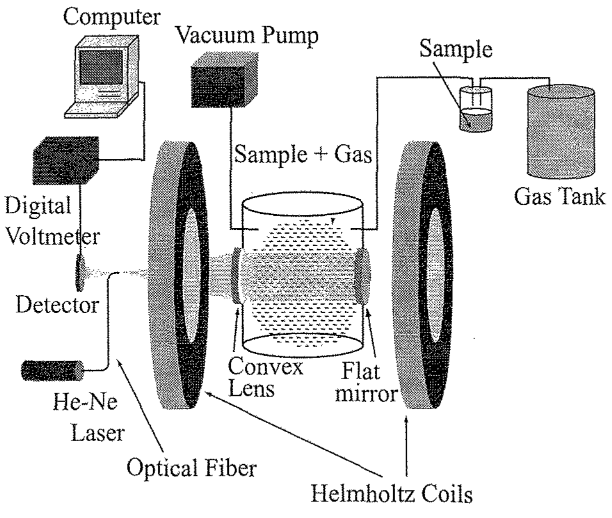

Fig.4 Apparatus developed to observe magnetic alignment below T=100K

5. DISCUSSION

The temperature to perform magnetic-alignment could be reduced to the order of T=10K by improving the efficiency of a thermal shield of the chamber described in Fig.4, and by replacing cold nitrogen gas with cold He gas. Various attempts are made to apply the effect of magnetic alignment on material-processing as mentioned before[2,4,11-13]. The large reduction of field intensity to achieve magnetic-alignment by decreasing temperature to T=10K may increase the practicability of such attempts. Magnetic alignment of non-ferromagnetic grains is generally considered to occur only in a strong magnetic field above several Tesla at present[1,2-5,11-13], since the $\Delta\chi$ values were generally small for diamagnetic nonmetallic materials.

The development of the apparatus shown in Fig.4 is a technical step forward to study dust-alignment mechanism in the star formation region, by reproducing the process in the dense-cloud condition having the temperature of about 10K[8,9,14,15]. Information on cosmic-field in the dense-cloud is a base to understand star and planet evolution; mechanism of dust alignment is still debatable in this region.

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