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Efficiency of Magnetic Alignment Detected for Non-Magnetic Insulators in Terrestrial and in Micro-Gravity Condition

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A novel method to detect small magnetic anisotropy $\Delta\chi$ of a solid body was proposed and confirmed using micro-gravity condition. $\Delta\chi$ of a sample floated in micro-gravity could be obtained by observing the rotational motion of the sample caused only by the magnetic torque. Restoring force of a fiber suspending the crystal, which had been the standard to measure $\Delta\chi$ in the conventional methods, has prevented the improvement of $\Delta\chi$ sensitivity. The c-planes of graphite single-crystals, stabilized in micro-gravity, showed rotational-oscillations with respect to field direction. Periods of oscillation followed the theoretically expected dependence of field intensity, moment of inertia and diamagnetic anisotropy. The observation is a step to improve sensitivity of measuring magnetic anisotropy considerably.
Key words: rotational oscillation of solid body induced by magnetic-field in micro-gravity, graphite, diamagnetic anisotropy, magnetic torque measurement, measurement of magnetic anisotropy in micro-gravity

1.INTRODUCTION

Diamagnetic $\Delta\chi$ values were obtained recently for various basic oxides such as forsterite[1], orthoclase[2], KDP, gypsum[3], $Mg(OH)_2$, muscovite[4] and corundum[5] using a newly developed method[6]. The values were interpreted consistently by assigning a finite amount of $\Delta\chi$ on the individual bonding orbital composing the crystal[1,3,5]. Many of the unmeasured oxides, generally composed chemical bonds, were expected to cause magneto-rotation at finite field intensity due to diamagnetic anisotropy according to the model. Data accumulation was necessary, in order to clarify the overall tendency of diamagnetic anisotropy of inorganic nonmetals. The values could not be detected by the above method for many of the oxides.

Magnetic alignment of micron-sized diamagnetic particles dispersed in fluid medium were reported for organic and inorganic nonmetals[7,8] such as fibrin[8], lysozyme[9], graphite[10], clay, mica[11] or corundum.[12] The alignment is caused by the field-induced anisotropy energy induced in the particles; the diamagnetic $\Delta\chi$ values are essential in analyzing the alignment process quantitatively. $\Delta\chi$ value of the material in quest is too small to be detected by the conventional methods in many cases.

The present report concerns with the technique developed to detect the small $\Delta\chi$ values of diamagnetic materials, based on the field-induced rotational-oscillations observed successfully for graphite crystals in micro-gravity condition[13].

2. EXPERIMENTAL

$\Delta\chi$ measurements were generally based on a principle first developed by Krishnann and Banergee[14]; the magnetic torque induced by anisotropy energy was measured by the restoring force of a fiber suspending the sample. The direction of the magnetically stable-axis rotated freely in the horizontal plane. The rotational equation for a sample, having a magnetic anisotropy $\Delta\chi$ [emu/g], is described as,

$$I(d^2\theta/dt^2) = -B^2 m\Delta\chi \sin 2\theta - (D/\ell)\theta. \qquad (1)$$

Here θ is the direction between $\boldsymbol{B}$ and the stable-axis. The moment of inertia and the mass of the sample are described by I and m, respectively. D and ℓ denote the tensional rigidity and the length of the fiber, respectively. The sensitivity of $\Delta\chi$ is limited by (D/ℓ) in the above methods. The sensitivity was improved by diminishing the term of restoring force to be negligible compared to that of the magnetic anisotropy energy[15]. The most direct way to realize further improvements of the sensitivity, using this principle, is to exclude the fiber from the system.

Fig.1 shows the sectional view of the apparatus developed to examine the principle mentioned above. The apparatus was designed to be loaded on a drop capsule at Micro-gravity Laboratory of Japan (Toki, Gifu, Japan)[13]. Rotational-oscillations were observed for a graphite single-crystal having different geometries. The sample was placed on a mobile sample stage initially placed at the center of a vacuum chamber. The stage had a slope which was inclined 45 degrees with respect to the horizontal plane. The samples were formed into rectangular prisms; a set of parallel planes of the prism were parallel to the magnetically-stable c-plane. The plane was placed parallel to the inclined slope of the stage. Static micro-gravity was applied on the system for 4.5 seconds. The stage was removed in the vertical direction after the achievement of micro-gravity leaving the sample at its initial position. A

Helmholtz-coil generated static field of 0.046T simultaneously. The chamber was evacuated to 4×10^{-4} Pa during the experiment in order to exclude the effect of turbulence of the gas due to the fast movement of the sample stage.

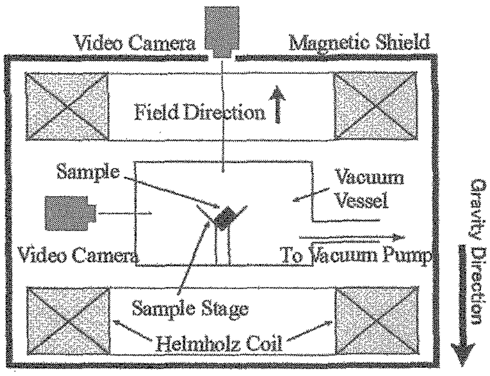

Fig.1 Sectional view of the apparatus loaded on a drop capsule[13].

Fig.2 shows visual images of a sample in micro-gravity taken before and after the removal of the stage. The block shaped sample is floated at its original position after the stage is removed. Periods of the rotational oscillation $\tau(\theta_0)$ observed for the graphite samples, were measured from visual images as seen in Fig.2. θ_0 is the angle of amplitude which was 45° in the experiment. $\tau(\theta_0)$ is calculated by inserting D=0 in eq.(1) as

$$\tau(\theta_0) = 2\pi(I / m\,\Delta\chi)^{-1/2} B^{-1} (1 + \theta_0^2/4 + ---). \qquad (2)$$

$\Delta\chi$ can be obtained from τ, B, m and I from the above equation, without the use of D and ℓ. The measured $\tau(\theta_0)$ value was 0.74±0.13 sec which agreed fairly well with the calculated values using eq.(2); τ=0.85 sec. This agreement confirmed the efficiency of the new principle of measuring $\Delta\chi$ proposed above. The published diamagnetic anisotropy of graphite $\Delta\chi$= 2.37 x 10^{-5} emu/g was used in the comparison[16].

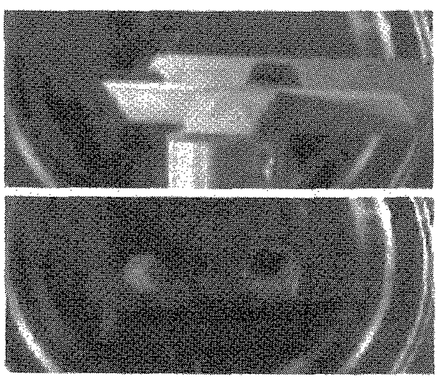

Fig.2 Visual image of graphite prism floated in micro-gravity[13].

3. DISCUSSIONS

Magnetic rotations of non-ferromagnetic materials have been studied intensively on micron-sized particles for both organic and inorganic materials as mentioned before[7]. The field induced anisotropy energy originating from the magnetic anisotropy $\Delta\chi$ of the material causes the magnetic alignment. The phenomenon has been successfully applied on material processing recently, such as crystal growth[9] or the production of polycrystalline materials with preferentially oriented crystal axes[12]. It is necessary to know the exact $\Delta\chi$ value of the material in order to analyze these process precisely, however the $\Delta\chi$ value of the material in quest is too small to be detected by the conventional methods in many cases. The new method enables quantitative analysis of the above mentioned alignment phenomena. Published $\Delta\chi$ values of diamagnetic-oxides will increase considerably using the present method, which lead to the evaluation of magnetic-alignment efficiency assumed for non-cubic diamagnetic-oxides in general. It is seen from the eq.(2) that smaller $\Delta\chi$ values could be detected by increasing the magnitude of B or τ.

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