ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 18(3), 308-310 (2013) http://dx.doi.org/10.4283/JMAG.2013.18.3.308

Field-Induced Translation of Single Ferromagnetic and Ferrimagnetic Grain as Observed in the Chamber-type μG System

Kento Kuwada[1], Chiaki Uyeda[1]*, Keiji Hisayoshi[1], Hideaki Nagai[2], and Mikito Mamiya[2]

[1]*Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[2]*National Institute of Advanced Industrial Science and Technology, Tsukuba Central 5, Tsukuba, Ibaraki 305-8565, Japan*

(Received 5 June 2012, Received in final form 26 October 2012, Accepted 26 October 2012)

Translation induced by the field-gradient force is being observed for a single ferromagnetic iron grain and a ferrimagnetic grain of a ferrite sample ($CuFe_2O_4$). From measurements on the translation, precise saturated magnetization of M_S is possible for a single grain. The method is based on the energy conservation rule assumed for the grain during its translation and the grain is translated through a diffuse area under micro-gravity conditions. The results of the two materials indicate that a field-induced translation of grain bearing spontaneous moment is generally determined by a field-induced potential $-mM_SH(x)$ where m denotes the mass of sample. According to the above translations, the detection of M_S is not interfered by any signals from the sample holder. The M_S measurement does not require m value. By observing translations resulting from field-induced volume forces, the magnetization of a single grain is measurable irrespective of its size; the principle is also applicable to measuring susceptibility of diamagnetic and paramagnetic materials.

Keywords : saturated magnetization, field gradient force, iron, ferrite, chamber-type μG experimental system, magnetic grain, magnetic ejection

1. Introduction

The necessity of understanding the magnetic property of a single grain has increased in various fields of magnetic science. With the reduction of sample size, the detection of magnetization becomes difficult due to the increasing effects of interfering signals emitted from the sample holder. Mass measurement of sample becomes difficult with the reduction of size. A method to detect magnetization of the mm-sized diamagnetic particle was recently proposed for solving the above mentioned problems [1]. When a diamagnetic grain of mass m is released in the area of static fields with negligible effects of gravity or viscous drag, the translation of the grain occurs by field gradient force $m\chi_{DIA}H(dH/dx)$; hereby, the field decreases monotonously along a x-axis, and diamagnetic susceptibility per unit mass is denoted as χ_{DIA}. It is expected that the motion generally occurs on diamagnetic solids, as the material generally possesses an intrinsic χ_{DIA} value. According to a Newton's motional equation, the acceleration a for the above translation is independent to m of the particle. Hence, a is uniquely determined by the intrinsic χ_{DIA} of material within a given field distribution.

The above translation was recently observed for sub-millimeter-sized particles of graphite and magnesia which had different χ_{DIA} values (graphite: -5.1×10^{-6} emu/g, magnesia: -2.1×10^{-7} emu/g) [2]. The translation was analyzed in terms of an energy conservation rule described as $-½m\chi_{DIA}H_0^2 = ½mv_R^2$; where H_0 denotes field intensity at initial sample position; v_R is the velocity of grain at a point where $H = 0$. From the above equation, χ_{DIA} is directly obtained from H_0 and v_R as, $\chi_{DIA} = -v_R^2H_0^{-2}$. A compact μG system, which could be introduced in an ordinary laboratory room, was developed according to the above observation in order to carry out the magnetization measurements of a routine process [2].

In the present study, the principle of the above-mentioned energy conservation rule was applied on the translation as observed for ferromagnetic and ferrimagnetic grains of mm-sizes. The practicability for detecting saturated

©The Korean Magnetics Society. All rights reserved.
*Corresponding author: Tel: +81-6-6850-5798
Fax: +81-6-6850-5480, e-mail: uyeda_caka@yahoo.co.jp

This paper was presented at the ICM2012, Busan, Korea, July 8-13, 2012.

magnetization M_S of a smaller sample is being discussed based on the observed results.

2. Experimental

Translations of magnetic grains in a monotonous direction of increasing fields were observed for iron and ferrite (CFe_2O_4) grains under the μG condition produced by short chamber-type drop shafts with a length of 1.5 m [2]. The duration of μG inside a drop box was ~0.5 seconds with residual gravity of 10^{-2} G. Schematic view of the experimental setup installed inside a drop box is shown in Fig. 1. The sample holder was opened after 0.01 seconds passed from the beginning of the μG condition, and was released in a diffuse gas medium with negligibly small initial velocities. The sample was translated inside a glass tube. The resistance caused by viscosity was reduced to a negligible level by maintaining internal pressure of the tube at about 100 Pa. The field gradient was created by a pair of NdFeB magnetic plate (size = 50 × 50 × 10 mm). The surface magnetic flux density of the magnetic plate was 0.2021 T. During the field-induced translation, the grain proceeded in an area in which the field intensity was higher than 0.15 T. Therefore, saturated magnetization M_s was attained from the measured grains throughout the translation, and the magnitude of magnetization did not depend on the number of magnetic domains contained in the grain. The motions of samples were recorded by high-speed camera (CASIO EXILIM EX-F1). Its frame rate and spatial resolution were 1200 fps and 200 ppi, respectively. According to the observed images of the high-speed camera, the effects of residual gravity on the motion of grain were negligibly small as compared to that caused by the field gradient force.

Operational tests of the above-mentioned setup were performed in a drop shaft at the National Institute of Advanced Technology AIST [3], before performing the above-mentioned μG experiments in the chamber drop shaft. The AIST system had a μG duration of 1.35 seconds and a residual gravitational acceleration of below 50 Gal. The above operational tests confirmed that the μG duration of the short drop shaft constructed at Osaka University was long enough to record the images of the translation.

Table 1. Numerical data of samples prepared to measure *M*s in μG condition.

Material	*m* [g]	Measured [G·cm³/g]	Published [G·cm³/g]
iron	6.18×10^{-5}	225	218
ferrite ($CuFe_2O_4$)	4.82×10^{-3}	43.6	47.1

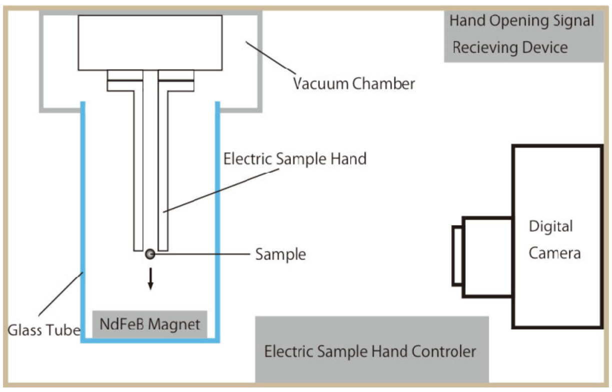

Fig. 1. (Color online) Schematic view of a setup to observe free translation of a magnetic grain that posses spontaneous magnetic moment.

3. Experimental Results

Under the above-mentioned conditions achieved in the μG experiment, the sum of kinetic energy and field-induced energy of the translating grain is conserved throughout the field-induced translation. Assuming that the grain is translated along a *x*-axis, the above-mentioned conservation rule at an arbitrary position x_i is described as:

$$\tfrac{1}{2} m v(x_i)^2 - m M s H(x_i) = const. \quad (1)$$

Here, the sample velocity and field intensity at position x_i is defined as $v(x_i)$ and $H(x_i)$, respectively. The experimental $v(x_i)$ values are determined from the images obtained by

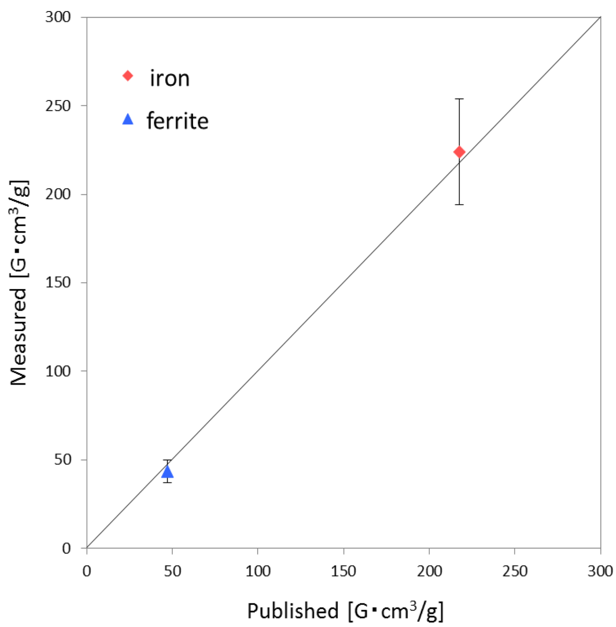

Fig. 2. (Color online) Saturated magnetization *M*s of a single grain compared with their published values.

the high-speed camera. Relationship between x_i and $H(x_i)$ was measured prior to the μG experiment. It is deduced from eq. (1) that *M*s is equivalent to

$$Ms = \{v(x_1)^2 - v(x_2)^2\}/\{H(x_1) - H(x_2)\}, \quad (2)$$

where $x = x_1$ and $x = x_2$ denote two arbitrary positions of the translating grain.

As described in Table 1 and in Fig. 2, the M_S value obtained from eq. (2) agrees fairly well with their published values for both iron and ferrite ($CuFe_2O_4$). It is considered that error of experimental *M*s shown in Table 1 and in Fig. 2 are caused by the uncertainty of determining the sample position from the images recorded by the high-speed camera. The ambiguity of sample position arises because ferro- and ferri-magnetic samples have large translation velocities caused by the attractive gradient forces. In order to reduce errors from the observed M_S value, the attempt to detect the translation by a higher frame rate is now in progress.

4. Discussion

The advantages of measuring a small sample using the above method are as follows. Firstly, the measurement is not interfered by signals emitted from the sample holder, because the sample is simply released into the μG space. Secondly, mass measurement of samples is unnecessary for the new method; it is difficult to detect *m* below 10 μg within an ordinary laboratory. Provided that the translational motion of samples is observable, magnetization can be measured for samples with limitlessly small sizes [1]. The technique proposed in the present report may be adopted as a new type of routine method as to analyze the magnetic grain, since the short drop-shaft is easily installed in an ordinary laboratory. The conventional μG facilities require a longer working time and the single running cost is considerably high for a routine magnetic analysis [3]. As mentioned before, M_S values of iron and ferrite ($CuFe_2O_4$), determined from the field-induced translations, were both consistent with their published values [4]. It is noted that iron has one of the largest *M*s value among ferromagnetic and ferrimagnetic materials, whereas ferrite ($CuFe_2O_4$) has one of the smallest. Accordingly, the results of Table 1 and Fig. 2 indicate that a field-induced translation of a ferromagnetic or ferrimagnetic grain is generally determined by a field-induced potential energy-$mM_SH(x)$, and that their motion is independent to mass of the particle within a given field distribution.

It was previously reported that the χ_{DIA} values obtained by field-induced translation of diamagnetic materials generally agree with the published χ_{DIA} values from two orders of magnitude, which indicated that the energy conservation rule is generally approved for diamagnetic particles [1, 2, 5]. It is expected that magnetization of a solid particle is measurable by a unique principle based on the free motion caused by a magnetic volume force, irrespective of its magnetic category. Observation is now required for the translation of paramagnetic particles, as to examine the standard of the above-mentioned energy conservation rule with regards to solid materials. The setup described in Fig. 1 is applicable for the above observation, since paramagnetic particles are expected to be accelerated in the direction of increasing fields.

References

[1] C. Uyeda, K. Hisayoshi, and S. Kanou, Jpn. Phys. Soc. Jpn. **79**, 064709 (2010).
[2] C. Uyeda, K. Hisayoshi, and S. Kanou, J. Phys. **48**, 2893 (2010).
[3] T. Iwakami and M. Nokura, J. Jpn. Soc. Microgravity Appl. **23**, 186 (2006).
[4] R. Guputa, Landort Bornstein New Series II 445 (1983).
[5] C. Uyeda, K. Hisayoshi, and S. Kanou, J. Phys. **48**, 2893 (2010).