# Evaluation of magnetic susceptibility difference of coagulated particles for crystal alignment

Kazuhiko Iwai

# Evaluation of magnetic susceptibility difference of coagulated particles for crystal alignment

IWAI Kazuhiko[1]

[1] Hokkaido University Kita 13 Nishi 8, Kita-ku, Sapporo, Hokkaido, 060-8628, JAPAN

*Corresponding author : iwai@eng.hokudai.ac.jp*

**Abstract**
Elicitation of crystallographic anisotropy is one of the promising methods for formation of functional materials because it enhances physical, chemical, mechanical and/or biological natures. Magnetic alignment is one of the powerful method of crystal alignment with magnetic susceptibility difference, in which operating parameters such as minimum intensity of the magnetic field and alignment time depend on the magnetic susceptibility difference. Thus, evaluation of the magnetic susceptibility difference of particles used as a raw material is essential for optimization of the crystal alignment process. However, it is different from that of a single crystal because particles used as a raw material is usually poly-crystals and/or coagulated, and it might have distribution. In this paper, evaluation of distribution of the magnetic susceptibility difference of bismuth particles has been investigated.

**Key words :** crystal alignment, magnetic susceptibility difference, particles

**Introduction**
Crystal alignment is a powerful method for producing functional materials with crystallographically anisotropic nature. For example, crystallographically aligned graphite strongly enhances heat flow because thermal conductivity of graphite in a,b-axis is about two hundred times larger than that in c-axis. Thus, a lot of materials such as ceramics and polymers have been slip cast under the imposition of a magnetic field to achieve crystal alignment. In this process particles or powders have been mainly used as a raw material. Their magnetic susceptibility difference in magnetically major axis and magnetically minor axis is different from that of single crystal because they might coagulate and they might be poly-crystal. Because magnetic susceptibility difference highly affects the minimum intensity of a magnetic field and alignment time in an alignment process, evaluation of distribution of magnetic susceptibility difference is essential for optimization of the alignment process. We evaluated the effective magnetic susceptibility difference distribution of bismuth particles using the measurement of in situ crystal-alignment behavior in the presence of a static magnetic field.

**Experimental**
Bismuth with a rhombohedral crystal structure was chosen as a sample material because it has a relatively large magnetic susceptibility difference of $5.3*10^{-5}$(-). Granular bismuth particles with a few mm size were grinded in a mortar to make them small particles. Median diameter of grinded particles were 12.5μm.

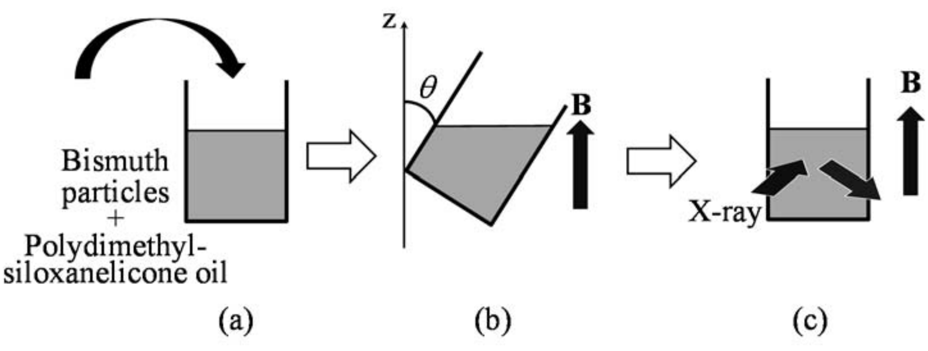


Fig.1 Experimental procedure

A slurry composed of grinded bismuth particles and liquid polydimethylsiloxane with viscosity of 50 Pa.s was inserted into an acrylic vessel as shown in Fig. 1(a). Then the vessel was inclined with an angle of 45 degrees from the gravitational direction under the imposition of a 1T vertical static magnetic field as shown in Fig. 1(b), and was kept for a while for magnetic alignment of the bismuth particles. In the next step, the aligned angle of the vessel was changed from 45 degrees to 0 degree as soon as possible, and X-ray was emitted into the vessel through the one of its side surface, which was made of thin polymer film to minimize the decay of X-ray, and reflected X-ray intensity was measured by the detector for evaluation of the peak intensity of bismuth (110) plane as shown in Fig. 1(c). Detail of the experimental procedure is mentioned in reference [1]. Because the c-axis is magnetically major axis, it becomes parallel to the magnetic field direction under the imposition of a magnetic field. That is, planes parallel to the c-axis such as (110) plane also become parallel to the magnetic field direction if a magnetic field is imposed. Thus the (110) plane peak intensity can be considered as an index of the bismuth particle alignment.

A particle alignment behavior under the imposition of a magnetic field can be theoretically expressed as follows.

$$\tan\phi = \tan\phi_0 exp\left(-\frac{t}{t_E}\right) \tag{1}$$

$$t_E = \frac{6\eta\mu_0}{\Delta\chi_e B^2} \tag{2}$$

where B is magnetic flux density, t is time, $t_E$ is relaxation time, $\Delta\chi_e$ is effective magnetic susceptibility difference of a particle, $\phi$ is angle between magnetically major axis and magnetic field direction, $\phi_0$ is initial angle, $\eta$ is viscosity of a surrounding liquid, $\mu_0$ is magnetic permeability in vacuum, respectively.

Magnetic susceptibility difference can be calculated using equations (1) and (2) by substituting the measured alignment time. In this experiment, the measured (110) bismuth plane peak intensity gradually increased and finally became constant at time, $t_F$ as shown in Fig. 2. The reason for this is mentioned below. Driving force of a bismuth particle alignment under the imposition of a magnetic field is magnetic torque while resistant force of the alignment is viscous torque caused by a fluid motion surrounding the particle. The former depends not only on the coagulating condition of the bismuth particles but also number, size of crystals constituting a particle, while the latter depends on the shape and coagulating condition of the bismuth particle. Therefore, alignment time of each particle is different, and some particles aligns quickly while some particles aligns slowly, and finally their magnetically major axis becomes parallel to the magnetic field direction.

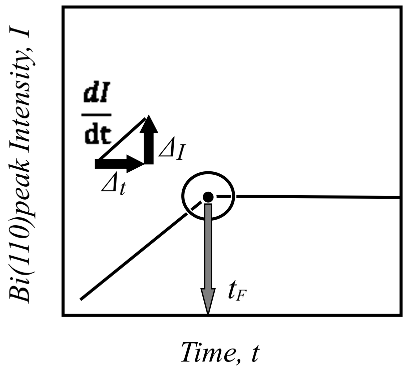


Fig.2 Time dependency of bismuth (110) peak intensity

A small increase in the peak intensity, dI in a small time between t and t+dt corresponds the amount of the particles having effective magnetic susceptibility difference of $\Delta\chi_e$ , which is calculated using equation (3).

$$\Delta\chi_e = \frac{1}{t}\frac{6\eta\mu_0}{B^2}[ln(\tan\phi_0) - ln(\tan\phi)] \tag{3}$$

Thus, the relation between the effective magnetic susceptibility difference and its ratio in the particles can be evaluated. Relative magnetic susceptibility difference, $\Delta\chi_r$ defined as equation (4) is introduced for easy understanding of magnetic property of the bismuth particles.

$$\Delta\chi_r = \frac{\Delta\chi_e}{\Delta\chi} \tag{4}$$

The obtained distribution of the relative magnetic susceptibility difference in this experiment is shown in Fig. 3. Minimum of the relative magnetic susceptibility difference was 0.2 and maximum was unity in this experimental condition. Thus, some particles had a magnetic property similar to that of a single crystal while some particles were coagulated and/or had shapes with large viscous resistance. And for alignment of all the particles, it takes a few times longer time than single crystals because about 40% of the particles have the relative magnetic susceptibility of around 0.3. This is useful information for crystal alignment using a magnetic field.

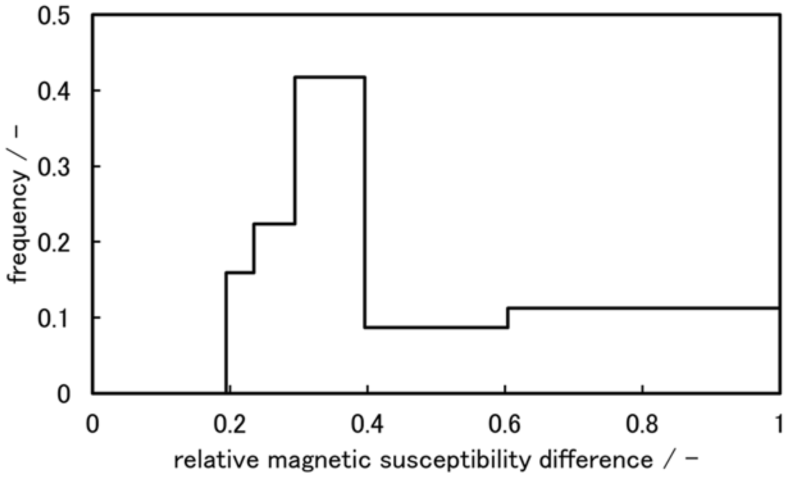


Fig.3 Distribution of relative magnetic susceptibility difference

**Conclusions**

Effective magnetic susceptibility difference of grinded bismuth particles in magnetically major axis and magnetically minor axis was evaluated. This is useful information for optimization of crystal alignment process using a magnetic field.

**Reference**


[1] Takenori KOHAMA, Hiroki TAKEUCHI, Manabu USUI, Jun AKIYAMA Jun, Sung Mun-Gyu, Kazuhiko IWAI, Shigeo ASAI, Materials Transactions, 48(2007), 2867-2871