Visualization of magnetic dipolar interaction based on scanning transmission X-ray microscopy

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Abstract. Using scanning transmission X-ray microscopy (STXM), in this report we visualized the magnetic dipolar interactions in nanocrystalline Nd-Fe-B magnets and imaged their magnetization distributions at various applied fields. We calculated the magnetic dipolar interaction by analyzing the interaction between the magnetization at each point and those at the other points on the STXM image.

1. Introduction
Nd-Fe-B magnets have recently attracted much attention as they have become increasingly used [1] and intensively examined [2, 3, 4, 5, 6]. In nanocrystalline Nd-Fe-B magnets, whose particle size is less than the single-domain size, magnetic dipolar interactions become essential in magnetization reversal processes. However, the significance of dipolar energy in these magnets is not yet understood, because a quantitatively measuring dipolar energy in magnetic materials is difficult. Therefore, we consider that it is important to visualize the magnetic dipolar interaction for revealing the nature of the magnetization reversal processes, and demonstrate a visualization of the magnetic dipolar interaction in permanent magnets using scanning transmission X-ray microscopy (STXM).

In STXM, a Fresnel zone plate (FZP) focuses the X-rays to a diffraction-limited focus, and images are acquired by raster-scanning the sample through the focus while measuring the transmitted intensity with a relatively large X-ray detector. In our experiment, we used a FZP with an outermost zone width of 25 nm and a focus size (or spatial Resolution) of about 30 nm. Additionally, we used a combination of a central stop and an order-sorting aperture to block zero-order light not diffracted by the zone plate and higher-order light. The samples, mounted on TEM grids, are first held in the focal position of the beam. The sample is then scanned with respect to the focused soft X-ray beam using an interferometer-controlled piezo stage. Transmitted light is measured using a photomultiplier with a scintillator. Essentially, STXM is a microscope that takes advantage of the X-ray magnetic circular dichroism (XMCD) effect. Because the XMCD effect is proportional to the magnetization of a specific element and is sensitive to the projection of the magnetization along the direction of photon propagation, the STXM image of the magnetic contrast shows the real space distribution of element-specific
magnetization with high spatial resolution. Therefore, STXM is a powerful tool to investigate the magnetic microstructure of Nd-Fe-B magnets [7].

In this paper, we analyzed the STXM image of the magnetization distribution with a special attention to the direction perpendicular to the surface. We calculated the potential energy of the magnetic dipolar interaction between the magnetization at each point and those at the other points on the STXM image in order to obtain the distribution of the dipolar energy. Finally, we visualized the magnetic dipolar interaction in the nanocrystalline Nd-Fe-B magnets at remanent states after applying 0, 1, 2, 4, 6, and 10 kOe.

2. Formalism
To visualize the magnetic dipolar interaction energies, we must calculate them from the magnetization distribution, which can be obtained from the STXM image [8]. The potential energy of the magnetic dipolar interaction $U$ is given by

$$U = -\int \frac{\nabla \cdot \mathbf{M}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dV' + \int \frac{\mathbf{n} \cdot \mathbf{M}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dS'. \quad (1)$$

In this study, we assume the sample is thin enough to calculate the magnetization as $\mathbf{M} = (0, 0, m(x, y))$. By substituting $\mathbf{M} = (0, 0, m(x, y))$ into eq.(1), we obtain

$$U = -\int dV' \frac{\partial m(x', y')}{|\mathbf{r} - \mathbf{r}'|} + \int dS' \frac{\partial m(x', y')}{|\mathbf{r} - \mathbf{r}'|} \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$$

$$= \int_{-a}^{a} dx' \int_{-b}^{b} dy' \int_{-c}^{c} dz' \frac{(z - z')m(x', y')}{((x - x')^2 + (y - y')^2 + (z - z')^2)^{3/2}}, \quad (2)$$

where $\mathbf{r} = (x, y, z)$ is the coordinate of the observation point, $\mathbf{r}' = (x', y', z')$ is the coordinate of the source point, $2a$ is the width of the sample in the $x$ direction, $2b$ is the width of the sample in the $y$ direction and $2c$ is the thickness of the sample. The relation between the magnetic dipolar interaction energy $E_d$ and the magnetic field $\mathbf{H}$ is given by

$$E_d = -\frac{1}{2} \int \mathbf{M} \cdot \mathbf{H} dV = -\frac{1}{2} \int m(x, y)H_z dV, \quad (3)$$

where $H_z$ is the $z$ component of $\mathbf{H}$. On the other hand, the relation between $U$ and $\mathbf{H}$ is given by $\mathbf{H} = -\nabla U$. Therefore, we can obtain $E_d$ as the function of $U$ as follows:

$$E_d = \frac{1}{2} \int dx \int dy \ m(x, y) \int dz \frac{\partial}{\partial z} U(x, y, z)$$

$$= \frac{1}{2} \int dx \int dy \ m(x, y) (U(x, y, c) - U(x, y, -c)). \quad (4)$$

From eq.(2), the term of $U$ in eq.(4) is given by

$$U(x, y, c) - U(x, y, -c)$$

$$= \int dx' \int dy' \ m(x', y') \int dz' \left[ \frac{c - z'}{(r_{xy}^2 + (c - z')^2)^{3/2}} - \frac{-c - z'}{(r_{xy}^2 + (-c - z')^2)^{3/2}} \right]$$

$$= \int dx' \int dy' \ m(x', y') 2 \left[ \frac{1}{r_{xy}^2} - \frac{1}{r_{xy}^2 + (2c)^2} \right], \quad (5)$$

where $r_{xy} = \sqrt{(x - x')^2 + (y - y')^2}$ is the length between the observation point and the source point. By using eq.(4) and eq.(5), we can visualize the distribution of the dipolar energy as shown in Fig.1(b) from the STXM image of the magnetization distribution as shown in Fig.1(a).
Figure 1. (a) STXM image of the magnetization distribution in the nanocrystalline Nd-Fe-B magnet. The scale unit is normalized to be equal to 1 at the maximum value. (b) Distribution of the magnetic dipolar interaction energy obtained from (a). The thickness of the sample is 60 nm.

3. Results

By using the method shown in Fig.1, we visualize the magnetic dipolar interaction in the nanocrystalline Nd-Fe-B magnet from the STXM image. We can obtain the two-dimensional magnetic dipolar interaction energy \( E_{d_{xy}} \), which also represents the density of the magnetic dipolar interaction energy \( E_d \) at \((x, y)\), by substituting eq.(5) into eq.(4)

\[
E_{d_{xy}}(x, y) = \frac{1}{2} \frac{m(x, y)}{2c} \int \int dx' dy' g(x, x') m(x', y'),
\]

Figure 2. Distribution of the dipolar energy for applied fields of 0, 1, 2, 4, 6 and 10 kOe in the nanocrystalline Nd-Fe-B magnet. The thickness of the sample is 60 nm. The dipolar energy is high in white areas and small in black areas.
where
\[
g(x, x') \equiv 2 \left( \frac{1}{r_{xy}} - \frac{1}{\sqrt{r_{xy}^2 + (2c)^2}} \right),
\]
(7)

\(x = (x, y)\) is the coordinate of the observation point on the \(x\)-\(y\) plane, and \(x' = (x', y')\) is the coordinate of the source point on the same plane. In Fig.2, we show the visualized magnetic dipolar interaction in nanocrystalline Nd-Fe-B magnet at remanent states after applying 0, 1, 2, 4, 6, and 10 kOe. When the applied field approaches the coercivity field (\(\sim 10kOe\)), the total dipolar energy decreases. This behavior suggests that the decreased dipolar energy contributes to the stability of permanent magnets against the applied field.

4. Summary
We demonstrated a visualization of the magnetic dipolar interaction in a nanocrystalline Nd-Fe-B magnet using STXM. Using those images, we calculated the potential energy of the magnetic dipolar interaction between the magnetization at each point and those at the other points on the STXM image. Therefore, we obtained the distribution of the dipolar energy and found that the total dipolar energy decreases when the applied field approaches the coercivity field (\(\sim 10kOe\)). This behavior suggests that the decreased dipolar energy contributes to the stability of permanent magnets against the applied field. Our results show that visualizing the magnetic dipolar interaction is important for observing the development of dipolar energy in magnetization reversal processes and helps to reveal the nature of those processes.

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