Depth dependence of spin-specific magnetic hysteresis loop observed by magnetic Compton scattering

Since magnetic-field-dependent magnetization measurement is the most basic experimental technique for investigating magnetic materials, there are many magnetization measurement methods. The superconducting quantum interference device (SQUID) and vibrating sample magnetometer (VSM) are the most famous tools for observing the average magnetization curve of magnetic materials. X-ray magnetic circular dichroism (XMCD) is a useful method that has element selectivity and is extremely sensitive to surface magnetism. There are many methods for observing the magnetization curve, although magnetic Compton scattering (MCS) is the only method that has the potential to separate and investigate the magnetization curves of ferromagnets with sizes on the order of centimeters from the surface to the internal region.

MCS is one of the powerful methods of investigating the bulk magnetic properties of ferro- or ferrimagnets. MCS reflects only the spin magnetic moment. The magnetic field dependence of the magnetic effect of MCS represents the spin magnetization curve, in other words, the spin-specific magnetic hysteresis (SSMH) loop [1,2]. In this study, we present a novel application of MCS to measure the depth dependence of the SSMH loop [3]. This technique is realized by scanning X-rays with a vertical beam size of 10 μm. We demonstrate the depth dependence of coercivity in a neodymium magnet. The coercivity around the surface of the neodymium magnet degrades upon mechanical cutting and polishing.

The depth dependence of SSMH loops was measured on the high-energy inelastic scattering beamline of SPring-8 **BL08W**. The incident circularly polarized X-ray energy was monochromatized to 182.6 keV with a Si (620) monochromator. The degree of circular polarization was about 0.55. The X-ray beam size was determined to be 10 μm in the vertical direction and 1 mm in the horizontal direction using a four-quadrant slit. Scattered X-rays were detected using a 10-segmented Ge solid-state detector (Ge-SSD) with a scattering angle of 178°. The momentum resolution was 0.43 atomic units (a.u.). The sample was set in a quick reversible superconducting magnet with a magnetic field between –2.5 and 2.5 T. The reversal time from –2.5 to 2.5 was 7 s. The magnetization direction was taken to be parallel to the scattering vector. We can obtain the SSMH curve from the magnetic effect as a function of magnetic field. For example, to obtain the magnetic effect at H = X T, the sample was first saturated by applying the highest magnetic field (H = 2.5 T) and then the target magnetic field (X) was applied to the sample. Next, the lowest magnetic field (H = –2.5) was applied to saturate the sample and then the target magnetic field (–X) was applied to the sample. Then, the magnetic effect at H = X T was obtained as $(I_X - I_{-X})/(I_X + I_{-X})$, where I_T and I_{-X} are the integrated intensities of the magnetic Compton profile (MCP) at X T and –X T, respectively. The SSMH loops were measured in different regions from the surface to the inside by changing the vertical sample position where X-rays were irradiated. When the X-rays are at the edge of the sample, the SSMH loop represents the surface region. When the X-rays are at the center of the sample, the SSMH loop is dominated by the internal region. Note that the SSMH loop near the center position of the sample also includes the surface perpendicular to the incident X-rays. However, the effect is negligible because of the large penetration depth. Since MCS uses high-energy incident X-rays to enhance the magnetic effect of MCP, MCS has a large penetration depth. To demonstrate the depth dependence of the SSMH loop, a commercial neodymium magnet was used as a sample. The dimensions are 2×2×4 mm^3, and the long direction is parallel to the easy magnetization axis. All the measurements were carried out under vacuum at room temperature.

Figure 1 shows a schematic illustration of the depth dependence measurements of SSMH for the neodymium magnet. When the incident X-rays are at 1 or 3, the SSMH loop represents the surface region. When the X-rays are at 2, the loop is dominated by the internal region.

Figure 2 shows the depth dependence of SSMH loops, where 0.94 and –0.94 denote the surface regions and 0 is the center of the magnet. The vertical axis represents the magnetic effect, which is

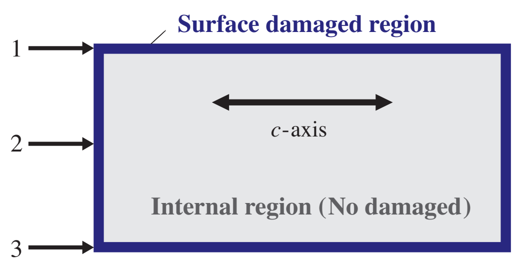

Fig. 1. Schematic illustration of the depth-dependent measurement of SSMH for the neodymium magnet.

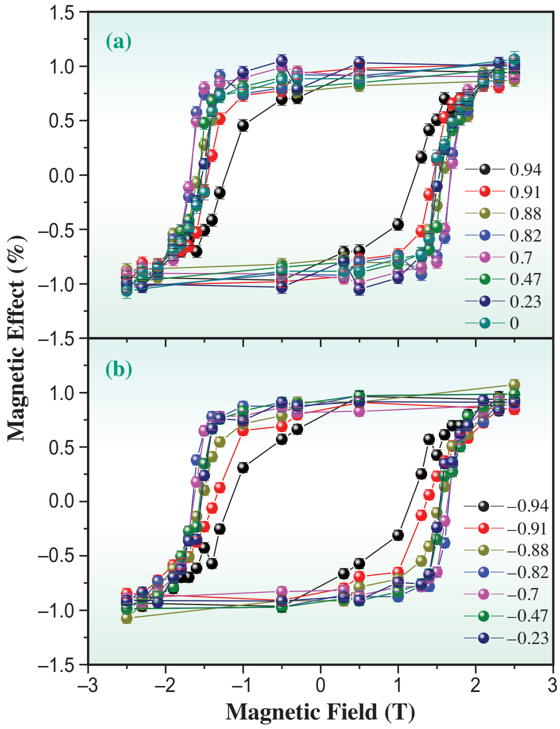

Fig. 2. Depth dependence of SSMH loops at **(a)** positive and **(b)** negative vertical sample positions.

proportional to the spin magnetization. The saturated spin magnetization is approximately constant, while the coercivity in the surface region decreases after surface treatment. To clarify the depth dependence of coercivity, we obtained the coercivity value by fitting a liner function to the SSMH data around its zero-cross point, as shown in Fig. 3. The demagnetization region extends to about 120 μm. Since the thickness of the surface damaged layer has been reported to be about 5 μm, this result shows that the effect of the narrow surface damaged layer extends to a deep region. The coercivity gradually decreases toward the center and is minimum at the center of the magnet. Kronmüller's equation is used to explain the coercivity of neodymium magnets and indicates that the coercivity is reduced by microstructural detects and/or the demagnetization field. Assuming that the microstructural defects are constant, we have concluded that the decrease in coercivity in the internal region may have been caused by the demagnetizing field. We expect that the present application of MCS will be a promising tool for magnetization measurement.

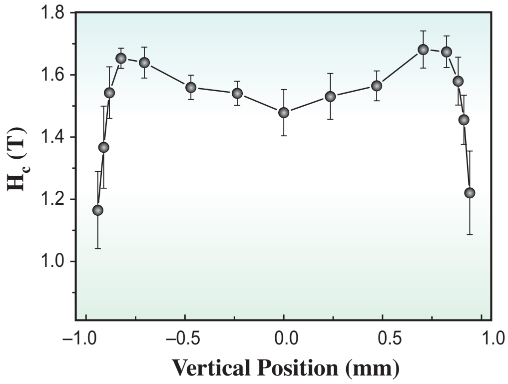

Fig. 3. Depth dependence of coercivity along the vertical sample position.

Naruki Tsuji

Japan Synchrotron Radiation Research Institute (JASRI)

Email: ntsuji@spring8.or.jp

References

[1] M. Itou *et al.*: Appl. Phys. Lett. **102** (2013) 082403.
[2] A. Agui *et al.*: J. Synchrotron Rad. **17** (2010) 321.
[3] *N. Tsuji, H. Sakurai and Y. Sakurai: Appl. Phys. Lett. **116** (2020) 182402.*