Deep Magnetic Structural Analyses within Soft Magnetic Materials Using Neutrons

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The advancement of soft magnetic materials hinges on the control of magnetic structures. However, the limited penetration of light, X-rays, and electrons restricts observations to surface and cross-sectional areas. Here, we demonstrate that utilizing multi-scale observation techniques with neutrons offers a valuable approach for evaluating deep magnetic structures in soft magnetic materials, paving the way for enhanced material performance.

Keywords: small-angle neutron scattering; ultra-small-angle neutron scattering; neutron Bragg-edge imaging

1. Introduction

Recently, there has been intensive research directed towards the advancement of soft magnetic materials for carbon neutral society. The key is the control of magnetic structures. However, in soft magnetic materials, magnetic structures manifesting at the surface due to demagnetizing fields from surface poles or process-induced surface strains often diverge significantly from those within the interior. This represents a considerable divergence from crystalline structures where internal states can be directly observed via cross-sectional examination. However, optical, X-ray, and electron beams employed for the structural analyses suffer from limited penetration in magnetic materials containing iron, resulting in information acquisition being confined to the surface or ultra-thin films. Consequently, deep magnetic structures have typically been inferred from surface information captured with these probes, along with the total magnetization (average value) and numerical simulations. As magnetic structure control continues to advance, such indirect estimations will reach its limits. In contrast, neutrons exhibit substantial penetration capabilities, thereby allowing for the elucidation of deep magnetic structures. Nonetheless, neutron scattering methods, while central to fundamental magnetism, have seen relatively limited utilization in the applied magnetics sectors. In this study, we investigated nanocrystalline ribbons and ferrite sintered cores using small-angle scattering, ultra-small-angle scattering, and Bragg-edge imaging, aiming to develop a multi-scale evaluation method for deep magnetic structures within soft magnetic materials.

2. Results and discussion

[mm scale and Å scale)] Wound ferrite sintered cores with a thickness of 13 mm were irradiated with polarized neutron pulses in an operando state. The magnetization distribution, parallel or antiparallel to neutron polarization, was directly detected from the map of the transmission spectra. Furthermore, from the magnetic Bragg edge, microscopic magnetic structures were identified, revealing it to be a ferrimagnetic state where the B sublattice magnetization aligns with the magnetic field direction [1].

[nm Scale and μm Scale] Nanocrystalline soft magnetic ribbons of NANOMET were subjected to small-angle and ultra-small-angle neutron scattering measurements following aging heat treatments. Within the small-angle scattering regime, a clover-leaf-shaped intensity distribution was occasionally observed, indicative of a spin misalignment magnetic structure at the nanoscale [2]. In contrast, within the ultra-small-angle scattering regime, a shift in the position of the profile's hump towards the high-q side was observed as a consequence of aging. This phenomenon is interpreted as a broadening of the direct beam resulting from multiple scattering, accompanying the subdivision of magnetic domains.

References

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[2] H. Mamiya, et al., IEEE Magn. Lett. **14** (2023) 7100105.

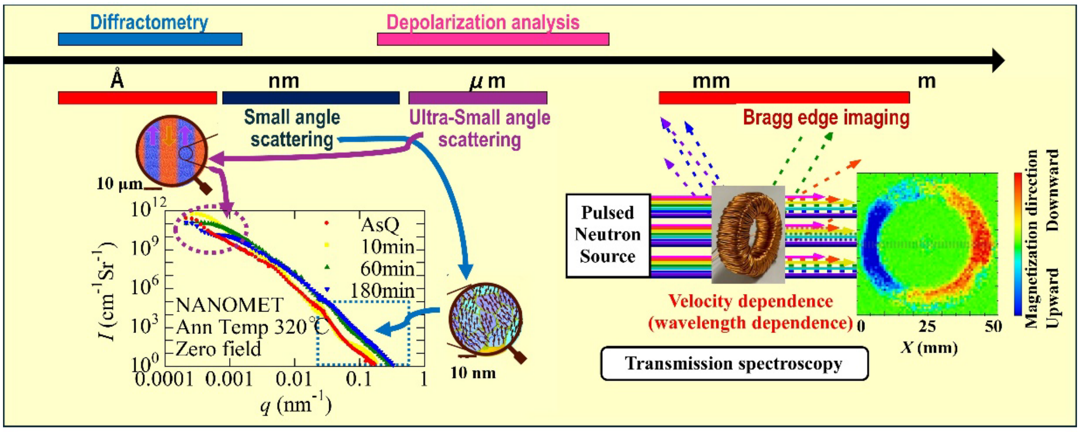

Figure 1: Multi-scale observation with neutrons for evaluating deep magnetic structures in soft magnetic materials.