Precision improvement in electron holography: application of information science to magnetic structure analysis

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Electron holography, which is a method related to transmission electron microscopy (TEM), can be a tool for the magnetic domain structure analysis, as it enables magnetic flux mapping in a nanometer-scale resolution. Actually, some of the authors [1)] have attained the atomic-scale resolution in the flux mapping from an oxide crystal, as it will be briefly mentioned in this symposium. For the applications to materials science and engineering, the other essential factor is "precision" of the magnetic flux density measurement. Importantly, the precision of electron holography depends on the image quality of "hologram" which is made of interference fringes of the incident electrons. (The hologram provides information about the phase shift of the incident electrons which traverse a magnetic specimen.) Although a long-time electron exposure can be an effective way to improve the image quality of holograms, it induces undesired specimen drift during data collection, surface contaminations, radiation damage, and other such problems. We have employed several techniques of information science and/or data science to improve the image quality of holograms. An essential technique is of noise reduction from holograms which were collected in a short exposure time (to suppress the undesired events caused by a long-time exposure). Midoh *et al.* [2)] introduced Markov property into the process of noise reduction using the wavelet transform and thresholding. Based on this modeling, they established a criterion for the separation of noise from weak signal in the holograms. The noise reduction improved the precision in phase analysis by 4-5 times as compared with the value from the original (unprocessed) hologram. In addition to this modeling, for another route of the noise reduction, we employed machine learning and the other methods of image processing to carry out the averaging of many holography observations.

Electron holography was applied to the magnetic flux density measurement from a narrow grain boundary produced in a 0.1% Ga-doped Nd-Fe-B sintered magnet [3)]. Because of the methods of precision improvement, the uncertainty in phase detection was reduced to $2\pi/210$ rad. The result is better than the value ($2\pi/80$ rad) attained in the previous electron holography study which revealed the presence of ferromagnetic grain boundaries in a commercial Nd-Fe-B magnet subjected to the optimal heat treatment [4)]. A sophisticated electron holography study [3)] allowed the magnetic flux density measurements as a function of positions along the grain boundary region: see Fig. 1. The observations provide useful information about the magnetic and/or chemical inhomogeneity in the grain boundary region in the 0.1% Ga-doped Nd-Fe-B magnet.

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Reference

1) T. Tanigaki *et al.,* manuscript in preparation.
2) Y. Midoh *et al.,* Microsc. **69** (2020) 121.
3) Y. Cho *et al.,* Scripta Mater. **178** (2020) 533.
4) Y. Murakami *et al.,* Acta Mater. **71** (2014) 370.

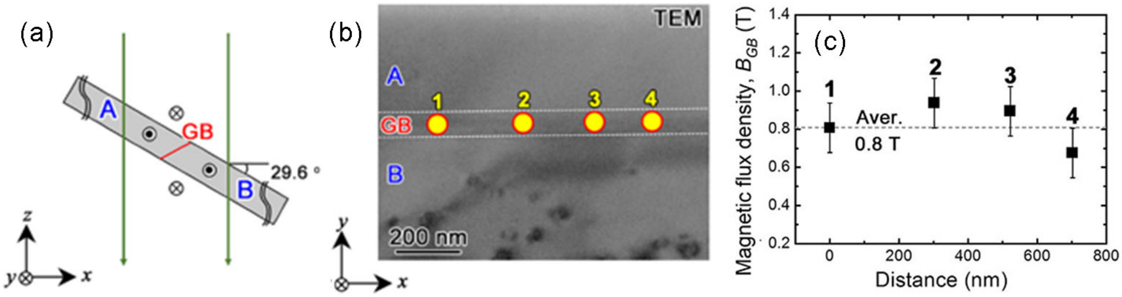

Fig. 1 Magnetic flux density measurements from the grain boundary (GB) in 0.1% Ga-doped Nd-Fe-B sintered magnet. (a) Schematic representation of the cross-section of thin-foil specimen, made of two $Nd_2Fe_{14}B$ grains A and B. (b) TEM image of the thin-foil specimen. Since the plane of GB was tilted away from the incident electron, the projection provides a wide GB region (~90 nm): refer to the area indicated by the white lines. (c) Magnetic flux density measurements from the points 1-4 in (b).