Transmission electron microscopy of magnetite at low temperature

Takeshi Kasama[1,*], Richard J. Harrison[2], Masahiro Nagao[3], Nathan S. Church[2], Joshua M. Feinberg[4], Yoshio Matsui[3] and Rafal E. Dunin-Borkowski[1]

[1] Center for Electron Nanoscopy, Technical Univ. of Denmark, Kongens Lyngby, Denmark

[2] Dept. of Earth Sciences, Univ. of Cambridge, Cambridge, U.K.

[3] Advanced Materials Laboratory, National Institute for Materials Science, Tsukuba, Ibaraki, Japan

[4] Institute for Rock Magnetism, Dept. of Geology and Geophysics, Univ. of Minnesota, Minneapolis, U.S.A.

The Verwey transition in magnetite is associated with an order-of-magnitude increase in magnetocrystalline anisotropy and a change in easy axis from cubic <111> to monoclinic [001] below ~120 K. Numerous studies have suggested that magnetic domain walls in magnetite can interact with the ferroelastic twin walls that form at low temperature because the monoclinic [001] direction can lie along any cubic <100> direction. However, the nature of these interactions remains controversial and the crystal structure, Fe^{2+}/Fe^{3+} distribution and magnetic properties of magnetite at low temperature are poorly understood.

We have used conventional and precession electron diffraction in the transmission electron microscope (TEM) to determine the ordering of Fe^{2+} and Fe^{3+} on octahedral sites in magnetite at low temperature and to show that the space group is monoclinic *Cc* with a small distortion from cubic symmetry. We find that the choice of monoclinic *c*-axis is affected by the strength of the magnetic field of the microscope objective lens.

We have also used off-axis electron holography and Lorentz imaging to study the nucleation and motion of magnetic domain walls and transformation twins in synthetic multi-domain magnetite during cycling through the Verwey transition. We observe clear interactions between magnetic domain walls and twin domain walls. Most of the twin domains have uniaxial magnetic domains along the monoclinic [001] direction. Whereas most 180° magnetic domain walls that intersect ferroelastic twin walls are mobile, some are pinned at the tips of needle twins. Zigzag magnetic domains, which are associated with *ab*-plane twinning along the *c*-axis and caused by slight deviations of the magnetic moments from the *c*-axis towards the intermediate *b*-axis, are observed only in thinner regions of specimens, suggesting that the specimen thickness may influence their formation. We also find magnetic domains formed by “strain-contrast-free” twins, which are not visible in conventional TEM images. Such submicron-sized magnetic domains with uniaxial anisotropy are observed widely and may have a strong influence on the low temperature magnetic properties of magnetite.

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*e-mail: tk@cen.dtu.dk