Quantitative imaging of magnetic microstructures at the nanometre scale using off-axis electron holography

R.J. Harrison[1], T. Kasama[2], E.T. Simpson[3] & R.E. Dunin-Borkowski[3]
[1]Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, U.K. [2]Frontier Research System, The Institute of Physical and Chemical Research, Hatoyama, Saitama, 350-0395, Japan. [3]Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, U.K.

Very few techniques are capable of providing quantitative information about the local magnetic induction in a material with nanometre spatial resolution. We have recently demonstrated that the transmission electron microscopy (TEM) technique of off-axis electron holography can be used to measure the magnetic induction in a naturally occurring titanomagnetite mineral sample with a spatial resolution of approximately 5 nm. Here we present an overview of the technique and its application to the quantitative measurement of magnetic induction in minerals with nanoscale microstructures.

The technique of off-axis electron holography allows the measurement of the amplitude and phase shift of a high-energy electron wave that has passed through a sample in a TEM. A positive voltage is applied to an electron biprism (for example, a quartz wire coated with gold) to overlap an electron wave that has passed through the sample with one that has passed only through vacuum. Analysis of the phase shift (the local position) of the holographic interference fringes that form in the overlap region is used to provide the magnitude and direction of the electromagnetic field within the material quantitatively and non-invasively. The technique can be used to map long-range fields such as those between patterned magnetic nanostructures, and also more local fields such as those due to charge redistribution on an atomic scale at interfaces between materials. The phase shift of the electron wave is sensitive to the magnetic induction and the mean inner potential (MIP). By magnetising the sample in opposite directions in situ in the electron microscope, acquiring electron holograms of these oppositely magnetised regions, and finally subtracting the resulting phase images from each other during processing, the MIP contribution to the phase shift can be eliminated, leaving only the magnetic signal of interest. Contours can then be generated from this magnetic phase image to produce a map of the in-plane component of the magnetic induction in the sample. This approach relies on being able to reverse the direction of the magnetisation in the sample exactly, which is satisfied for certain sample geometries, such as chains of crystals.

Electron holography has been used to study negative exchange coupling at antiphase boundaries (APBs) in the ilmenite-hematite system, with the aim of determining the origin of self-reversed thermoremanent magnetisation (SR-TRM). Quantitative analysis of the phase shift shows that three distinct types of magnetic wall exist in quenched ilmenite-hematite. The first type corresponds to conventional free-standing 180° Bloch walls. These walls are free to move within the interior of an antiphase domain (APD) under the influence of an applied magnetic field. The second type forms when a 180° reversal in magnetization coincides exactly with the position of an APB. These walls are referred to as a 180° 'chemical' walls. The reversal of magnetization results from negative exchange coupling between adjacent APDs, and occurs without any out-of-plane rotation of the magnetic moments. A third type of magnetic wall appears when the negative exchange coupling between adjacent APDs is overcome at sufficiently large fields, forcing the magnetization in adjacent APDs to point in the same direction. We refer to these walls as 0° magnetic walls. The implications of these observations to the origin of SR-TRM are discussed.