1619
doi:10.1017/S1431927615008879 Paper No. 0808

Microsc. Microanal. 21 (Suppl 3), 2015

Comparison of Magnetic Domain Observation by Means of Magnetic Force Microscopy and Lorentz Transmission Electron Microscopy

S. Hua[1] and M. De Graef[1]

[1] Dept. of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh PA 15213, USA

With the emergence of scanning probe technology such as magnetic force microscopy (MFM), magnetic domain imaging has become relatively easy and fast compared to some of the more traditional observation techniques, such as Lorentz transmission electron microscopy (LTEM). MFM is based on a standard scanning probe microscope (SPM), but with an extra ferromagnetic layer deposited on the tip. The magnetostatic force or force gradient between a magnetic sample and a magnetic tip is recorded and the topographic background is subtracted out. The magnetic contrast obtained from MFM is representative of the stray magnetic field above the sample surface and is determined by the magnetization orientation of the tip. Thus, in order to fully describe the magnetic field distribution inside and around the sample, another domain observation technique must be combined with MFM. LTEM is a good candidate because it has similar spatial resolution [1] and is sensitive to the in-plane magnetic component inside the sample. With both MFM and LTEM results available on the same sample, quantitative magnetization profiles of a domain wall can be obtained in principle using a dedicated image processing approach. Then, quantitative magnetic information, such as the domain wall width (DWW), or potentially the more fundamental exchange parameter, can be determined from a combination of these two domain observation techniques.

The observation of the same magnetic domain structure using both MFM and LTEM was achieved using a single crystal of $\mathrm{Ni}_{49.9}\ \mathrm{Mn}_{28.3}\ \mathrm{Ga}_{21.8}$ (AdaptaMat Ltd, Finland). The sample was heat-treated to achieve a thermally induced multi-variant martensitic state prior to electropolishing [2]. Fig. 1(a) shows a Fresnel image taken on a Tecnai F20 FEG-TEM operated at 200 kV in Lorentz observation mode. Two kinds of martensitic variants can be found in this area, and each has a distinct magnetic domain structure. In variant I, the easy axis (tetragonal $[001]$) is oriented out of the plane, nearly normal to the sample, which results in a fine-scale maze-like domain structure due to the strong magnetostatic interactions which force the magnetization to rapidly change over short distances in order to minimize the stray field energy. In comparison, straight and more widely spaced magnetic domain walls are observed in variant II. This domain structure indicates that the magnetization direction and the easy axis are in the foil plane, and hence there is a low stray field surrounding these variants.

Fig. 1(b) shows a MFM image from an area close to that shown in Fig.1(a). The same wedge-shape martensitic variants are observed in the MFM phase image. The variants that display very little magnetic contrast correspond to variant II in the Lorentz image Fig. 1(a). This is because the magnetization of the MFM tip was perpendicular to the plane of the foil and the magnetization state inside variant II is mostly in-plane; thus, the out-of-plane component of the demagnetizing fields is very small and does not strongly affect the tip vibration state. In comparison, strong magnetic contrast is found in the other martensitic variant, which corresponds to variant I in Fig. 1(a). In these variants, because the magnetization in different domains is nearly perpendicular to the foil plane, the magnetostatic energy dominates and the flux closure forms a strong demagnetizing field above the variant. However, the domain structure in Fig. 1(b) is not as smoothly curving as the maze-like domain structure in Fig. 1(a). This likely indicates that the magnetization is not precisely perpendicular to the foil plane and the domain walls are likely tilted; in the LTEM images, this would only give rise to a slight broadening of the domain wall contrast.

For the LTEM observation mode, the electron phase shift due to the magnetic vector potential inside and surrounding the sample can be reconstructed from through-focus Fresnel images using the transport-of-intensity equation approach. This phase shift undergoes a linear change inside a uniformly magnetized domain and a non-linear change (with non-zero second derivative) across a domain wall, which we can use to determine the projected width of a domain wall. Using this approach, the average domain wall width in variant I of Fig. 1 was determined to be 17.5 ± 3 nm. However, this method assumes that the domain walls are strictly perpendicular to the foil plane. In Fig. 1(b), the MFM image indicates that the magnetization in some domain regions may not be perpendicular to the foil plane, which results in a somewhat discontinuous maze-like domain structure. Further analysis, including micromagnetic modeling, of these domain configurations will be presented. In summary, we have managed to observe the same magnetic domain structure corresponding to different martensitic variants in a Ni-Mn-Ga alloy foil using both LTEM and MFM techniques. In our ongoing work, we are attempting to correlate the domain wall width measurements from the LTEM observartion mode with those from the MFM mode, with as a final goal the experimental determination of the magnetic exchange constant of this material.

References:
[1] A. Hubert in ”Magnetic domains: the analysis of magnetic microstructures”, (Springer, New York)
[2] A. Budruk, C. Phatak, A.K. Petford-Long, M. De Graef, Acta Materialia **59** (2011), p.4895
[3] The authors acknowledge funding from the National Science Foundation, Grant NSF-DMR #1005330.

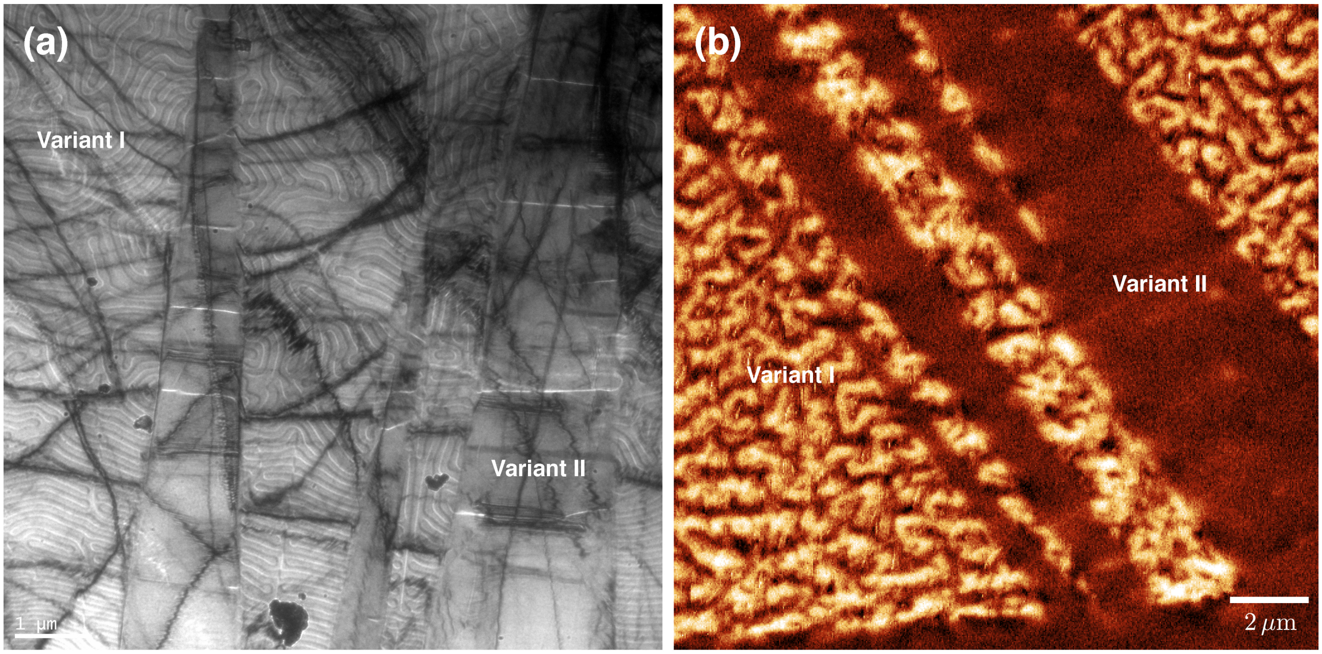

Figure 1. (a) Fresnel image of magnetic domain structure in a thermally treated multi-martensitic state NiMnGa thin foil. (b) MFM image of the same magnetic domain structure in the area close to Fig.1(a).