Novel magnetic domain structure of iron meteorite observed by photoelectron emission microscopy (PEEM)

Iron meteorites show an extraterrestrial pattern called the Widmanstätten structure (Fig. 1(a)). Their metallographic features have been of great benefit to planetary scientists in their study of the history of the solar system. On the other hand, they also show unique magnetic properties significantly different from those of common FeNi alloys. Namely, iron meteorites have remarkably large magnetic anisotropy and strong coercivity, but no explanation has been proposed for how these magnetic properties are associated with the Widmanstätten structure. The important basic question is how the spins of hard magnetic tetrataenite ($L1_0$-FeNi) thin films couple with the surrounding soft magnetic Fe-Ni alloys in the Widmanstätten structure. From the viewpoint of materials science, the heterogeneous structure near the boundary can be considered as a type of magnetic multilayer system composed of α-FeNi, $L1_0$-FeNi, and γ-FeNi (Fig. 1(b)). It is also remarkable that the crystallographic orientation of these FeNi phases maintains a certain relationship, in which the $\{110\}_\alpha$ axis maintains a parallel orientation to the $\{111\}_\gamma$ axis [1]. Here, we studied the magnetic properties of iron meteorites associated with the Widmanstätten structure for the first time.

Photoelectron emission microscopy (PEEM) was carried out to study the magnetic domain structure and metallographic structure of iron meteorites [2]. PEEM is a type of electron microscopy, that can reveal the chemical composition, bonding state, and magnetic domain structure at a resolution of several tens of nanometers. PEEM together with the magnetic circular dichroism (MCD) technique provides a magnetic domain image by the helicity reversal of circularly polarized light. PEEM together with the X-ray absorption fine structure (XAFS) technique provides lattice and composition information by the continuous scan of excitation photon energy. Although PEEM has been mainly used in the study of synthetic nanomaterials, it is also a powerful investigation tool for natural materials. Experiments were performed at beamlines **BL25SU** and **BL39XU**.

Figure 2(a) shows the obtained composition map in the interface region between the α- and γ-lamellae. The Ni composition in the γ-lamella rapidly increased toward the interface, and the crystallographic structure gradually changes from the bcc structure to the fcc structure as the Ni composition increases. Such structural alteration may be associated with the chemical composition suggesting that $L1_0$-FeNi is segregated at the boundary from the metallurgical viewpoint. The magnetic domain structure obtained in the same region is shown in Fig. 2(b). The magnetizations on both sides of the interface are aligned opposite to each other and orthogonal to the domain wall; this magnetic domain eventually forms a ''head-on'' structure. Such a magnetic domain structure is unfavorable for synthetic Fe–Ni alloys, because it requires a large amount of magnetostatic energy for a demagnetizing field. For a typical 180 domain structure, the magnetization is oriented parallel to the domain wall so as to reduce the static magnetic energy; thus, such a structure in iron meteorites is a unique magnetic domain.

To verify such a magnetic domain structure, we performed micromagnetic simulation, solving the Landau-Lifshitz-Gilbert equation for the Fe/$L1_0$-FeNi/Ni system. The magnetic domain structure is disarranged and a head-on magnetic domain structure is clearly revealed near the interface. According to the concept of technical magnetization, a magnetic domain structure is determined so as to minimize the total energy. The magnetic anisotropy energy of $L1_0$-FeNi is much larger than that of the surrounding soft

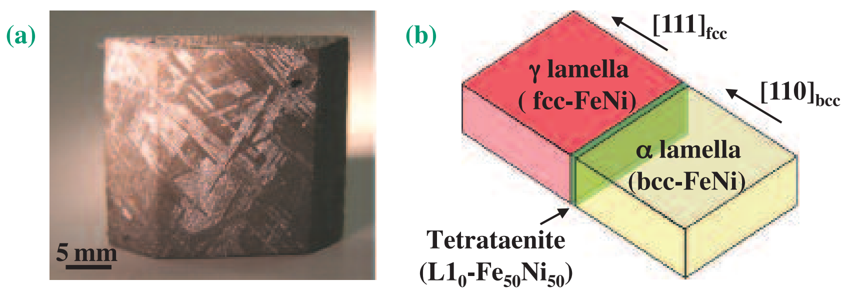

Fig. 1. Widmanstätten structure of iron meteorite **(a)** and model of structure in the interface region **(b)**.

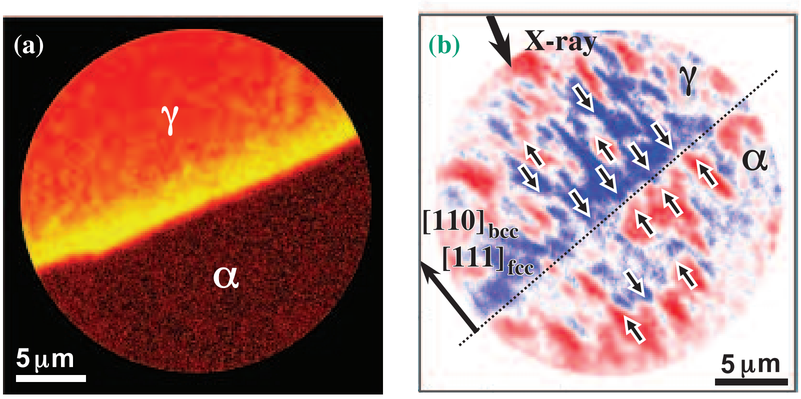

Fig. 2. Composition map **(a)** and magnetic domain image **(b)** in the interface region of iron meteorite obtained by PEEM.

magnetic Fe and Ni. The magnetization of $L1_0$-FeNi remains in the direction of an easy axis that produces the magnetic pole at the surface. To cancel the increase in magnetostatic energy at the surface, the magnetic moments of soft-magnetic Fe and Ni at both sides can be easily disarranged, resulting in the formation of a head-on magnetic domain structure (Fig. 3). Such a head-on magnetic domain structure is commonly reproduced for $L1_0$-FeNi films of various thicknesses; moreover, no head-on magnetic domain structure is observed for a simple Fe/Ni interface. It is finally concluded that head-on magnetic domains are induced by the $L1_0$-FeNi phase segregation at the boundary in the Widmanstätten structure.

It is also remarkable that the magnetic anisotropy energy of 3.2×10^5 J/m^3 in the $L1_0$-FeNi phase is significantly large compared with that in the common FeNi phase. From the viewpoint of reducing environmental impact, new important insights into the synthesis of the $L1_0$-FeNi phase have recently been attracting much attention [3]. The abundance of Fe and Ni opens a new possibility of rare-metal-free $L1_0$-type ferromagnets that will provide further magneto-electronic applications.

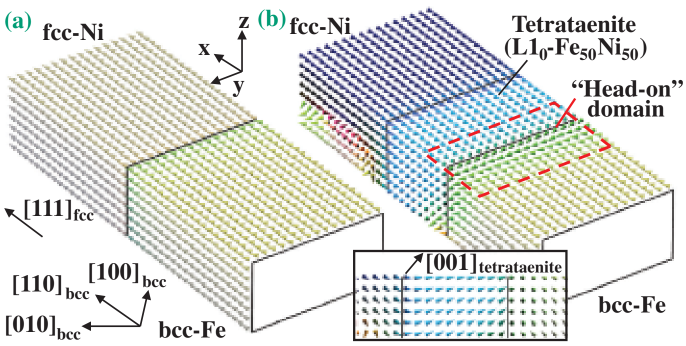

Fig. 3. Micromagnetic simulations of Fe/Ni and Fe/$L1_0$-FeNi/Ni.

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