2722 Microsc. Microanal. 28 (Suppl 1), 2022
doi:10.1017/S1431927622010248

Magnetic Domain Structure of Magnetite Particles in the Return Sample from Asteroid Ryugu by the Hayabusa2 Mission

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Carbonaceous chondrites, a type of primitive meteorite, contain magnetite particles, which is one of major carriers of iron in this type of meteorites. These magnetite particles have distinctive forms, such as plaquettes, which consist of less than 20 stacked disks, and framboids, which are raspberry-like clusters of magnetite particles (typically <1.5 μm). Typical size of plaquettes and framboids is from a few μm to <20 μm. It is known that magnetite particles are formed by aqueous alteration in asteroids, the parent bodies of meteorites [1]. The characteristic morphology of magnetite particles reflects the environment in which they were formed [2]. In addition, magnetite particles can be responsible for the remanent magnetization. Therefore, clarification of the reason for the characteristic morphology and the magnetic domain structure of magnetite particles can reveal the environment inside the asteroid and the nebular environment where the asteroid formed in the early stage of the formation of the solar system [3]. We have been using electron holography to observe the magnetic domain structure of magnetite particles to constrain the environment in which they form [2, 3]. Based on our previous findings, here, we analyzed magnetite particles brought back by Hayabusa2 from the asteroid Ryugu [4].

Rocks are known to acquire a remanent magnetization that reflects the environment in which they have been experienced. In the case of meteorites, they are exposed to the Earth's magnetic field for a long time after they fall, and it is difficult to trace their history from fall to analysis in most cases. Then, it is difficult to guarantee that the magnetic minerals retain their original magnetic domain structure. An assumption may be required for interpretation of the remanent magnetization. On the other hand, the sample collected by Hayabusa2 has a clear history from the time it was brought back to Earth in December 2020 to the time we observe it in the summer of 2021, and the years of exposure to the Earth's magnetic field are short. In addition, we know where and how the sample was collected on the surface of the asteroid Ryugu, the origin of the sample, and the temperature history is also clear [4, 5 and there in].

Hayabusa2 collected samples from two locations on the surface of the asteroid Ryugu [5, 6]: the first was collected by landing directly on the original surface and stored in Chamber A of a sample catcher. The second was collected by landing ~20-m north of an artificial crater created by firing a small impactor from the Hayabusa2 spacecraft [7] and stored in Chamber C of the sample catcher. More than 50% of the sample in the Room C has been expected to be collected from the sub-surface (<1.5 mm in depth) of the asteroid Ryugu [7]. The coarse grains recovered from Chamber A and Chamber C are labeled with the initial letters A and C and a four-digit number, respectively. We used the samples named A0063, A0064, C0002, C0023, C0040, and C0103 for our observation using electron holography.

We carefully maintained an external magnetic field environment of less than 50 μT from ISAS, JAXA, where the samples were maintained, until the observation of the magnetic domain structure using electron holography. In addition, all samples were stored and analysed without atmospheric exposure, except during loading and unloading the sample into the tabletop scanning electron microscope (SEM) where they were exposed to air for less than 15 seconds in total. First, a tabletop SEM (JCM-7000, NeoScope, JEOL) was used at a low acceleration voltage (5 kV) to find magnetite framboids suitable for observation based on morphology and compositional analysis. Ultrathin sections of the selected samples were prepared at -90°C using cryo- Focused Ion Beam (FIB; NB5000, Hitachi High-Tech). The samples were observed using a specially designed holography transmission electron microscopes (TEMs) with a magnetic field-free (<17 μT) sample stage. The holography TEMs used were the Hitachi HF-3300 with an acceleration voltage of 300 kV in the Fine Ceramics Center and the H-1200FT with an acceleration voltage of 1. 2 MV in Hitachi, Ltd.

After completing the magnetic field free observation, the sample was identified as magnetite by compositional analysis and electron diffraction pattern using a conventional TEM (JEM-F200, JEOL), and electron energy loss spectroscopy (EELS) analysis was performed to confirm the electronic state of iron and oxygen. The sample is still stored in the Ar glovebox (dew temperature of ~- 80^{o}C).

Figure 1 shows a TEM image of a thin section of a typical framboidal magnetite with ~1 μm in a fragment from the sample A0064. Strong contrast (black) region is tungsten layer deposited to prevent beam damage during FIB thinning. Corresponding magnetic flux distribution image of remanent magnetic state of the magnetites has been shown in Fig. 2. The holographic observation revealed that each particle has a concentric circular magnetic field (vortex structure). The characteristic vortex-like magnetic domain structure in the magnetite particles indicates that some of the magnetic flux leaks out of the particles. Such leakage fields are detected as remanent magnetization in conventional macroscopic measurements [e.g., 8]. Therefore, the magnetic domain structure and the formation environment of magnetite particles are expected to provide a partial understanding of the overall picture of the early solar system [9].

https://doi.org/10.1017/S1431927622010248 Published online by Cambridge University Press

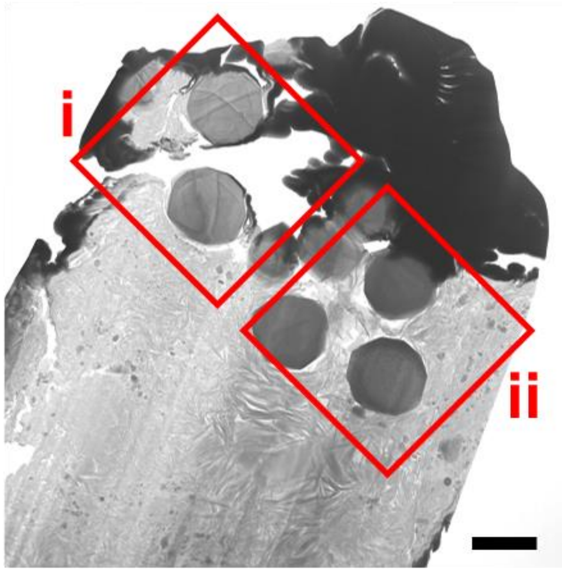

Figure 1. TEM image of a thin section of a magnetite framboid from the sample A0064 FO007 prepared by FIB. FO007 is one of the serial numbers assigned to particles presumed to have fallen out of the mother grain of A0064. Scale bar is 1 μm.

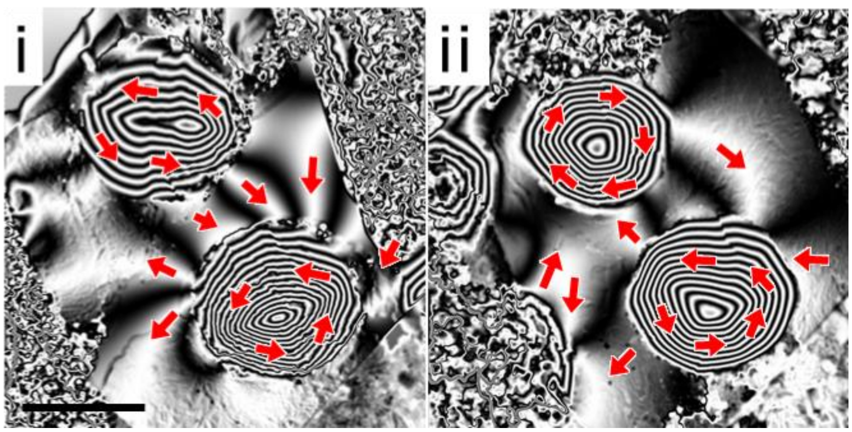

Figure 2. Magnetic flux distribution image of remanent magnetic state of magnetites corresponding to i and ii in Fig. 1 observed by electron holography. The red arrows show the direction of the magnetic flux. Half times the phase-amplified reconstruction for ii. Scale bar is 1 μm.

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