Microstructures of iron sulfide of Itokawa particles

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Introduction:

Space weathering has been referred to describe the collective processes that modify the optical properties, chemical compositions, and structures of materials on the surfaces of airless Solar System bodies [1]. Hayabusa spacecraft touched down to a S-type near-Earth asteroid 25143 Itokawa and recovered surface regolith particles, which are consistent with minerals contained in LL5-6 ordinary chondrite [2]. Analysis of Itokawa particles revealed nanoparticle-bearing rim, which are probably the major cause of alteration of reflectance spectra of Itokawa [3]. Prior to Hayabusa mission, the Near-Earth Asteroid Rendezvous (NEAR) mission's orbital study of S-type asteroid Eros revealed that change of reflectance spectra has been developing on Eros's surface similar to Itokawa's surface [4]. NEAR also discovered that Eros's surface appears to be strongly depleted in sulfur compared to ordinary chondrite [4]. However, sulfur depletion has not been obvious on Itokawa from remote-sensing observation and sample analysis so far. Sulfur in Itokawa samples is primarily bound in the form of iron sulfide [1], we investigated microstructures of iron sulfide of Itokawa particles in order to understand behavior of sulfur on airless bodies.

Experiments:

The four Itokawa particles were fixed with a 5 μm-diameter carbon fiber using glycol phthalate. The surface morphologies of the Itokawa particles were observed using a field-emission scanning electron microscope (Hitachi, SU6600) equipped with an energy-dispersive X-ray (EDX) spectroscopic detector (Bluker XFlash FladQUAD 5060FQ) at the Institute of Molecular Science, Japan. Regions of interest (ROI) were selected based on the FE-SEM observation, and electron-transparent sections including particle surface were prepared from the ROI using a focused ion beam (FEI, Helios G3 CX) at Kyoto University, Japan. The sections were observed using a field-emission transmission electron microscope (JEOL, JEM-2100F) equipped with an EDX system (JED-2300T) at Kyoto University.

Results:

Iron sulfides are visible as inclusions of olivine grains, adhered particles, and melt-splashes on the Itokawa particles. From surface observation using FE-SEM, we found needle-like structures protruding from the iron sulfide surfaces (Fig.1ab). The lengths of the needles range from several tenth nm to 1 μm. The needles often develop on porous iron sulfide surfaces (Fig.1ab). SEM-EDX analysis shows that the needles are composed of iron and they are deficient in sulfur (Fig.1c). The needles often contain minor nickel. So far, we lifted out FIB sections from a melt-splash of iron sulfide where needle-like structures develop on its surface. The melt-splash is an immiscible mixture of silicate and iron sulfide, covering an olivine grain. Fig. 1 shows a cross section of the melt splash of 50 nm in thickness including the needles. Elemental maps by TEM-EDX analysis clearly shows that the needle consists of iron and lacks in sulfur (Fig.1d). A TEM-selected area electron diffraction (SAED) pattern of the needle (Fig. 1f) indicates that the needle has a structure of body-centered cubic iron (α-iron). The iron sulfide layer is composed of amorphous structures, expect for regions nearby the iron needle. Crystalline pyrrhotite structure is developed in the vicinity of the iron needle. Beneath the iron sulfide layer, vesicular damage rims are developed on olivine surface, which might have been formed due to the implantation of solar wind hydrogen and helium [3]. The existence of vesicular rim indicates that olivine surface has been exposed to the sun over a period of time, before the melt splash attached to the olivine surface.

Discussions:

Remarkable surface morphology of iron sulfide such as iron needles have not been reported in previous analysis of Itokawa particles. On the other hand, prior observation of pyrrhotite grain of Itokawa particles reported that the outer 10-nm-wide zone is sulfur-depleted, including metallic iron grains (<5 nm) [5]. Mineral surfaces exposed to the space environment can be modified through space weathering by solar wind irradiation and impacts of micrometeorites. In previous studies, the feasibility of alteration of iron sulfide by space weathering effects have been examined experimentally [6, 7]. Laboratory studies on the chemical alteration of troilite by 4keV He ions simulating exposure to the solar wind and by nanosecond laser pulses simulating evaporation by micrometeorite impact showed that sulfur is depleted from troilite by these both effects [6] and iron layer of 2-3 nm in thick is identified after He ion implantation [7]. However, these experiments have not produced metallic iron needles as observed in this study. Prior experiments of heating troilite at near its eutectic temperature under H_2 gas flow showed that sulfur evaporates from troilite and iron residue is formed through incongruent evaporation [8]. This experiment showed that iron exists as irregular rods or sheet of micron meter in size. This could suggest that heating events such as meteoroid impacts together with implantation of solar wind hydrogen cause metallic iron needles on iron sulfide of Itokawa particles.

These heating events and ion implantation may lead to preferential loss of sulfur from Itokawa. X-ray fluorescence observations of Itokawa by the Hayabusa spacecraft did not find evidence for a large sulfur depletion on this S-class asteroid, as seen on Eros, though errors are large due to low solar activity during the orbital phases of the Hayabusa mission [9]. The microstructures of iron sulfide observed in this study could suggest that sulfur depletion processes are ongoing on Itokawa.

References:

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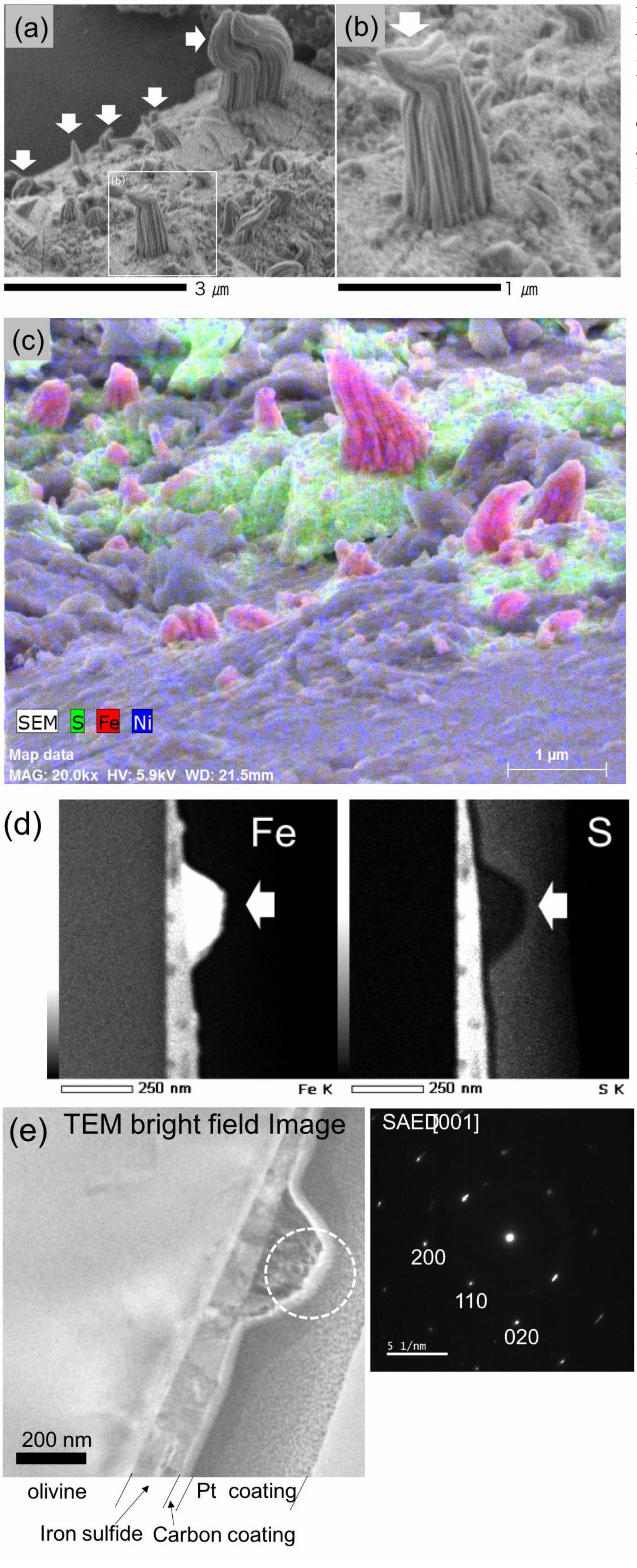

Figure 1 (a) (b) Secondary electron images of iron sulfide. Needle-like structures are indicated by arrows. (c) A SEM-EDX image of iron sulfide grains on olivine surfaces. (d) STEM-EDX images of a cross section of splash melt on olivine particle. A needle-like structure is indicated by arrows. (e) A TEM image and A SAED pattern of a needle-like structure.