

Nitridation of magnetite on the surface of C-type asteroid Ryugu.

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Introductions: JAXA's Hayabusa2 spacecraft brought back regolith samples from the C-type carbonaceous asteroid Ryugu [1,2]. Ryugu samples are composed of aqueously altered materials corresponding to CI carbonaceous chondrite meteorites. Because the Ryugu samples were collected from the space-exposed surface of Ryugu, they record the phenomena occurring at the airless surface of the carbonaceous asteroid. Materials on airless bodies are gradually modified by solar wind irradiation and micrometeorite impacts. This process is called space weathering. The major features of space weathering in Ryugu samples are dehydration of the phyllosilicate and reduction of iron in the phyllosilicates [3]. In this study, we focused on the surface modifications of magnetite in Ryugu samples. We report the surface modification of space-weathered magnetite and the discovery of iron nitride on the magnetite surface.

Methods: We examined three fine Ryugu grains, A104-021012, A104-028098, and A104-026006. These three grains were stored in a glove-box filled with purified nitrogen before the analysis. The grains are fixed on gold plates using epoxy resin, and were observed using scanning electron microscopy (SEM) to analyze their surface modifications. After the surface observation, electron-transparent sections were made from the grain surface using the focused ion beam system. The extracted sections were analyzed by scanning transmission electron microscopy (TEM/STEM).

Results: FIB sections from A104-021012 and A104-028098 contain assemblies of framboid magnetites with 500 nm to 1 μm in diameter. A FIB section from A104-026006 includes spherulitic magnetite with 10 μm in diameter. These magnetite grains coexist with the fine-grained matrix composed mainly of phyllosilicate. Their exposed surfaces show granular textures. STEM-EDS analysis showed that magnetite in A104-021012 has the distinct surface layer showing the high Fe/O ratio. Electron diffraction patterns from the iron-rich layer correspond to the body-centered cubic iron. Magnetite grains in A104-026006 and A104-028098 also have iron-rich layers at the surface. In addition, the iron-rich layers are rich in sulfur and nitrogen. Electron diffraction patterns from the iron-rich layer in A104-026006 indicate the bcc-iron metal and a cubic crystal that has the lattice parameter corresponding to roaldite (Fe_4N). Thin coating layers of silicon and magnesium are identified on the modified magnetite in A104-021012, A104-028098, and A104-026006.

Discussion: The increase of the Fe/O ratio and the formation of iron metals at the magnetite surface is likely due to the selective escape of oxygen from the surface caused by solar wind implantation and micrometeorite bombardments [6]. Sulfur and nitrogen would have been supplied to the exposed surfaces of magnetite. Iron nitrides have been identified in meteorites as nebular condensates or high-pressure products in iron meteorites. In contrast, iron nitrides in Ryugu grains are likely associated with space weathering of magnetite and may have been formed through surface processes on Ryugu. One possible source of the nitrogen is implantation of solar wind. We estimate that the exposure age of 10^5 years is necessary to accumulate solar nitrogen. This age is far longer compared to the longest solar wind exposure age of 3500 years for Ryugu samples [4]. Another possible source is nitrogen compounds included in impact vapors on Ryugu. Iron metal is highly reactive with ammonia gas that leads to the formation of iron nitrides. We calculated that nitridation of iron metals could have occurred when the surfaces are exposed to impact vapors with nitrogen contents higher than the CI composition. Ammonia-rich vapors can be produced from micrometeoroids including nitrogen-rich organic materials, and/or ammonium compounds, such as NH_4^+ salts.

References

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Keywords: Hayabusa2, Ryugu, Asteroid