Defect microstructure of pyrrhotite in regolith material returned from C-type asteroid 162173 Ryugu – evidence for shock metamorphism

Falko Langenhorst[1], Dennis Harries[2], Takaaki Noguchi[3], Toru Matsumoto[3,4], Akira Miyake[3], Yohei Igami[3], the Min-Pet "Sand" Team, and the Hayabusa2 Initial Analysis Core.

[1]*Institute of Geoscience, Friedrich Schiller University Jena; Carl-Zeiss-Promenade 10, D-07745 Jena, Germany;*
[2]*Luxembourg Institute of Science and Technology, European Space Resources Innovation Centre; Belvaux, Luxembourg;*
[3]*Division of Earth and Planetary Sciences, Kyoto University; Kitashirakawaoiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan;*
[4]*The Hakubi Center for Advanced Research, Kyoto University; Kitashirakawaoiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan*

Introduction. The Hayabusa2 mission successfully returned regolith materials from two sampling sites of the C-type Near-Earth Object (NEO) 162173 Ryugu [1]. Mineralogical characterization of samples revealed that aqueous alteration was an omnipresent process, which resulted mainly in the formation of phyllosilicates, carbonates, phosphates, and other phases forming under hydrous conditions [2]. Since Ryugu is an airless body whose surface is directly exposed to interplanetary space, it was also expected that regolith samples contain traces of space weathering (effects due to solar wind particle and micrometeoroid bombardments). Effects of solar wind bombardment were discovered in several samples [3,4], while traces of shock metamorphism are scarce [5], which is unusual considering the rubble pile nature of asteroid Ryugu.

Samples and methods. Ryugu samples from the two sampling sites were collected in separate chambers A and C of the sample catcher [2]. Within the activities of the Min-Pet "Sand" team, we have examined three samples from chamber A (A0058-T4, AP002-g03, AP007-g06), which probed the uppermost surface material of Ryugu. The three samples were first investigated by field emission scanning electron microscope (FE-SEM: JSM-7001F at Kyoto University). We then extracted electron-transparent sections of regions of interest on the Ryugu grains, using a focused ion beam (FIB) system (Helios NanoLab G3 CX at Kyoto University). The FIB sections were finally observed using analytical transmission electron microscopy (TEM, Tecnai G2 FEG at Univ. of Jena). Bright-field and dark-field TEM imaging techniques combined with selected area electron diffraction (SAED) were employed to characterize the defect microstructures.

Results. Among all the mineral grains in the three FIB sections, only a relatively large (9 x 4 µm dimensions) pyrrhotite grain from sample AP007-g06 turned out to exhibit a rich defect microstructure. This grain is only partially surrounded by phyllosilicates, where it displays well-developed faces parallel to (001), (010), and (011). At the free surface, the grain is however irregularly shaped and pitted. Our previous investigation revealed a systematic variation in the superstructure type towards the free surface with N values ranging from 4.0 (4C-pyrrhotite, $x \approx 0.125$) in the grain interior to 5.9 (close to 6C-pyrrhotite, $x=0.083$) at the surface [4].

Additionally, we observe a high density of dislocations in various geometric configurations pervading the entire grain. Straight, up to 1 µm long dislocations with dislocation lines parallel to [001] are most abundant (density up to 2×10^{13} m^{-2}), while dislocations reorganized in sub-grain boundaries and dislocation loops occur subordinately. The straight elongated dislocations are apparently glissile with 1/3[110](001) acting as slip system. Bright-field TEM images and SAED patterns indicate also the presence of multiple microtwins on the (001) plane throughout the entire grain. Sub-grain boundaries and dislocation loops occur in the vicinity of internal voids that might have been once filled with fluid.

Discussion. This overall rich defect microstructure of pyrrhotite implies that the grain was affected by various processes. The variation in the superstructure type below the irregular pitted surface was attributed to incipient space weathering, causing a loss of sulfur on the free surface and an inward diffusion of Fe into the grain interior [4]. Internal voids and dislocation loops are, however, likely defects produced during aqueous alteration. The activation of a large number of perfect dislocations and microtwins on the basal plane are a typical response of monosulfides to dynamic loading [7]. Although no crater is observed on the surface, we interpret these defects as clue to shock metamorphism affecting the entire grain.

References

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