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Nanomorphology of Itokawa regolith particles: Application to space-weathering processes affecting the Itokawa asteroid

Toru Matsumoto [a,*], Akira Tsuchiyama [b], Kentaro Uesugi [c], Tsukasa Nakano [d], Masayuki Uesugi [a], Junya Matsuno [b], Takashi Nagano [e], Akira Shimada [e], Akihisa Takeuchi [c], Yoshio Suzuki [c], Tomoki Nakamura [f], Michihiko Nakamura [f], Arnold Gucsik [g,h], Keita Nagaki [e], Tatsuhiro Sakaiya [e], Tadashi Kondo [e]

[a] *Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan*

[b] *Division of Earth and Planetary Sciences, Kyoto University, Kitashirakawaoiwake-cho, Sakyo-ku, Kyoto-shi 606-8502, Japan*

[c] *SPring-8/Japan Synchrotron Radiation Research Institute, Sayo 679-5198, Japan*

[d] *Geological Survey of Japan/National Institute of Advanced Industrial Science and Technology, Tsukuba 305-8567, Japan*

[e] *Department of Earth and Space Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka 560-0043, Japan*

[f] *Department of Earth Science, Tohoku University, 6-3, Aramaki Aza-Aoba, Aoba-ku, Sendai-shi, Miyagi 980-8578, Japan*

[g] *Department of Geology, University of Johannesburg, Johannesburg, 2600 Auckland Park, South Africa*

[h] *Konkoly Thege Miklós Astronomical Institute, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Hungary*

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Abstract

The morphological properties of 26 regolith particles from asteroid Itokawa were observed using scanning electron microscopes in combination with an investigation of their three-dimensional shapes obtained through X-ray microtomography. Surface observations of a cross section of the LL5 chondrite, and of crystals of olivine and pyroxene, were also performed for comparison. Some Itokawa particles have surfaces corresponding to walls of microdruses in the LL chondrite, where concentric polygonal steps develop and euhedral or subhedral grains exist. These formed through vapor growth owing to thermal annealing, which might have been caused by thermal metamorphism or shock-induced heating in Itokawa's parent body. Most of the Itokawa particles have more or less fractured surfaces, indicating that they were formed by disaggregation, probably caused by impacts. Itokawa particles with angular and rounded edges observed in computed tomography images are associated with surfaces exhibiting clear and faint structures, respectively. These surfaces can be interpreted by invoking different degrees of abrasion after regolith formation. A possible mechanism for the abrasion process is grain migration caused by impact-driven seismic waves. Space-weathered rims with blisters are distributed heterogeneously across the Itokawa regolith particles. This heterogeneous distribution can be explained by particle motion and fracturing, combined with solar-wind irradiation of the particle surfaces. The regolith activity—including grain motion, fracturing, and abrasion—might effectively act as refreshing process of Itokawa particles against space-weathered rim formation. The space-weathering processes affecting Itokawa would have developed simultaneously with space-weathered rim formation and regolith particle refreshment.

Keywords: Asteroid Itokawa; Regolith; Surface morphology; Space weathering

* Corresponding author.
E-mail address: tmatsumoto@planeta.sci.isas.jaxa.jp (T. Matsumoto).

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1. INTRODUCTION

The cumulative processes that alter the optical properties, chemical compositions, and structures of materials on the surfaces of airless solar system bodies are referred to as space weathering (Pieters et al., 2000). It has been proposed that space weathering is caused by irradiation by the solar wind and Galactic cosmic rays, as well as by micrometeoroid bombardments (Hapke, 2001; Clark, 2002). To date, studies of space weathering have mainly been conducted using lunar samples (Keller and McKay, 1993, 1997; Pieters et al., 2000; Hapke, 2001). Iron particles referred to as nanophase iron ($npFe^0$) are thought to produce the visible-to-infrared (VIS–NIR) optical features characteristic of space weathering: reddening, darkening, and attenuation of absorption bands. Lunar-type space weathering is expected to occur on S-type asteroids (Chapman, 2004). The formation of $npFe^0$ might cause a spectral change in ordinary chondritic material related to S-type asteroids, a notion that is supported by experiments (e.g., Sasaki et al., 2001; Loeffler et al., 2009) and observations of regolith breccias (Noble et al., 2010). Detailed information about the development of space weathering of S-type asteroids should be obtained through remote sensing of S-type asteroids and analysis of actual asteroid samples.

The Hayabusa spacecraft rendez-voused with asteroid 25143 Itokawa in 2005 and brought regolith samples, collected from its smooth terrain (MUSES-C), back to Earth in 2010 (Yano et al., 2006; Nakamura et al., 2011; Tsuchiyama, 2014; Yoshikawa et al., 2015). The Itokawa reflectance spectrum corresponds to that of S-type asteroids (Abe et al., 2006; Hiroi et al., 2006). An observed color variation is mostly attributed to different degrees of space weathering (Hiroi et al., 2006; Ishiguro, 2014). The surface of Itokawa consists of non-uniformly distributed boulders and regolith (Saito et al., 2006). Cratering structures on Itokawa of meter- to hundred-meter sizes have been identified (Saito et al., 2006; Hirata et al., 2009; Michel et al., 2009). Evidence of a re-arrangement of boulders and migration of regolith, possibly owing to impact or tidal shaking, has also been identified on Itokawa (Saito et al., 2006; Miyamoto et al., 2007). These features suggest that the materials on Itokawa's surface are still active; the movement of boulders and regolith is related to the observed color variation (Saito et al., 2006), suggesting that the degree of space weathering is closely related to the surface activity on Itokawa. Remote-sensing observations can hardly be used to examine the chemical and structural changes in minerals related to space weathering, which are expected to occur on micro- to nanometer scales. The recovered regolith samples should have micro- to nanometer-scale information about the importance of space weathering and offer insights into the relation between space weathering and surface activity on Itokawa.

Itokawa regolith particles consist of minerals corresponding to ordinary LL4–6 chondrites (Nakamura et al., 2011, 2014; Tsuchiyama et al., 2011, 2014; Yurimoto et al., 2011; Nakashima et al., 2013). The existence of noble gases due to implantation of the solar wind and spallation caused by Galactic cosmic rays show that the Itokawa particles stayed in regolith layers on the asteroid (Nagao et al., 2011; Meier et al., 2014). Space-weathered rims, including partially amorphous structures containing $npFe^0$, nanophase Fe oxide, and nanophase (Fe,Mg)S, have been observed on the surfaces of Itokawa particles using transmission and scanning transmission electron microscopy (TEM/STEM). It has been proposed that these space-weathered rims might have formed mainly through solar-wind irradiation rather than by micrometeoroid bombardments (Noguchi et al., 2011, 2014; Keller and Berger, 2014; Thompson et al., 2014; Matsumoto et al., 2015). VIS–NIR reflectance spectra of three Itokawa particles were obtained by Bonal et al. (2015); these particles appear to exhibit a variable extent of space weathering. Matsumoto et al. (2015) showed that blister structures on a space-weathered rim on the surface of an Itokawa particle, formed by accumulation of solar-wind particles, can be observed as spotted structures using a field-emission scanning electron microscope (FE-SEM). Systematic observation of the spatial distribution of the blisters will provide detailed insights into the development of space-weathered rims of Itokawa regolith particles. In particular, investigation of the relation between the blister distribution and other surface morphological features is important to reveal the relationship between spectral changes caused by space-weathered rim formation and various evolution processes of regolith particles on Itokawa.

Surface features have been observed using FE-SEM by Nakamura et al. (2012) for five Itokawa particles and by Matsumoto et al. (2015) for one particle. Nakamura et al. (2012) reported submicrometer-sized crater-like objects and tiny, flattened glass objects, which seem to be melt splashes. These earlier observations were obtained only for a limited number of particles. So far, a general classification and interpretation of the surface morphology of Itokawa particles on submicrometer scales has not yet been performed, nor has a study of the blister distribution. In previous studies, the three-dimensional (3D) structures of Itokawa particles were examined by X-ray microtomography (Tsuchiyama et al., 2011, 2014). However, as the spatial resolution of the surface shapes attainable using microtomography is limited (effectively $\gtrsim 1\ \mu m$), observations with higher resolution, such as those offered by FE-SEM, are required. Comparisons of the surface morphologies of Itokawa particles and of natural mineral fragments having experienced different degrees of shocking are helpful to accurately interpret the surface morphologies of the Itokawa particles. It is also important to compare with non-brecciated LL chondrites in order to investigate morphological features of lithified rocks corresponding to those of the Itokawa grains.

In the present study, the surface micro- to nanomorphologies of 26 Itokawa particles and LL5 chondrite samples, crushed and recovered from shock-experiment natural mineral grain samples, are examined using FE-SEM combined with a 3D structure analysis obtained by X-ray microtomography (Tsuchiyama et al., 2011, 2014) to understand the space-weathering processes on Itokawa, discuss the evolution history of regolith particles, and