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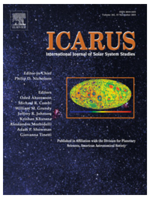

Population characteristics of submicrometer-sized craters on regolith particles from asteroid Itokawa

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ABSTRACT

We investigated impact crater structures on regolith particles from asteroid Itokawa using scanning electron microscopy. We observed the surfaces of 51 Itokawa particles, ranging from 15 μm to 240 μm in size. Craters with average diameters ranging from 10 nm to 2.8 μm were identified on 13 Itokawa particles larger than 80 μm. We examined the abundance, spatial distribution, and morphology of approximately 900 craters on six Itokawa particles. Craters with sizes in excess of 200 nm are widely dispersed, with spatial densities from 2.6 μm^2 to 4.5 μm^2; a fraction of the craters was locally concentrated with a density of 0.1 μm^2. The fractal dimension of the cumulative crater diameters ranges from 1.3 to 2.3. Craters of several tens of nanometers in diameter exhibit pit and surrounding rim structures. Craters of more than 100 nm in diameter commonly have melted residue at their bottom. These morphologies are similar to those of submicrometer-sized craters on lunar regolith. We estimated the impactor flux on Itokawa regolith-forming craters, assuming that the craters were accumulated during direct exposure to the space environment for 10^2 to 10^4 yr. The range of impactor flux onto Itokawa particles is estimated to be at least one order of magnitude higher than the interplanetary dust flux and comparable to the secondary impact flux on the Moon. This indicates that secondary ejecta impacts are probably the dominant cratering process in the submicrometer range on Itokawa regolith particles, as well as on the lunar surface. We demonstrate that secondary submicrometer craters can be produced anywhere in centimeter- to meter-sized depressions on Itokawa's surface through primary interplanetary dust impacts. If the surface unevenness on centimeter to meter scales is a significant factor determining the abundance of submicrometer secondary cratering, the secondary impact flux could be independent of the overall shapes or sizes of celestial bodies, and the secondary impact flux could have similar values on Itokawa and the Moon.

1. Introduction

Solar system objects without atmospheres are continuously exposed to hypervelocity impacts. Impact processes are considered to be among the fundamental agents causing the modification of surface geological features of airless bodies. They include impact cratering (e.g., Melosh, 1989), regolith formation (e.g., Melosh, 1989), regolith mixing, and migration (e.g., Robinson et al., 2001; Veverka et al., 2001; Miyamoto et al., 2007). In addition, microscopic meteoroid impacts contribute to changes in the optical properties, chemical composition, and structures of regolith surface material through impact melting, vaporization, and condensation processes, so-called 'space weathering' (e.g., Clark et al., 2002). Surface evolution caused by hypervelocity impacts can offer important clues to understanding the history of airless bodies in the solar system.

The Hayabusa spacecraft touched down on an S-type near-Earth asteroid, 25,143 Itokawa (Yano et al., 2006), and recovered regolith particles from its surface (Yada et al., 2014). Mineralogical and oxygen isotope properties of Itokawa particles are consistent with those of LL5–6 chondrite (Nakamura et al., 2011; Tsuchiyama et al., 2011; Yurimoto et al., 2011; Nakashima et al., 2013). Itokawa particles contain solar-wind gases and cosmogenic nuclei, implying that they remained on the asteroid's surface (Nagao et al., 2011). Partially crystalline rims containing nanoparticles provide evidence of space weathering effects on S-type asteroids, where solar-wind irradiation damage and implantation are the major causes of rim formation, whereas micrometeoroid impacts play only a minor role

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(Noguchi et al., 2011; Harries and Langenhorst, 2014; Keller and Berger, 2014; Noguchi et al., 2014; Thompson et al., 2014; Bonal et al., 2015; Matsumoto et al., 2015; Harries et al., 2016; Matsumoto et al., 2016). In addition, regolith activity on Itokawa—probably driven by impact processes—has been identified based on grain motion (Nagao et al., 2011; Matsumoto et al., 2016), fracturing (Tsuchiyama et al., 2011; Langenhorst et al., 2014; Matsumoto et al., 2016), and abrasion (Tsuchiyama et al., 2011). These previous studies have shown that Itokawa particles contain a record of the collective processes of regolith evolution on this small asteroid.

In previous studies, submicrometer-sized impact craters have been found on Itokawa particles (Nakamura et al., 2012; Harries et al., 2016; Matsumoto et al., 2016). These natural, small-scale craters can offer insights into the process of small-scale hypervelocity impacts, for which impact experiments in the laboratory have not yet yielded a comprehensive picture. In addition, these small craters can provide information about the unknown origin of the micrometeoroids bombarding Itokawa and the possible contribution to space weathering by submicrometer impacts (Harries et al., 2016). Craters with diameters from micrometers to a few tens of nanometers are generally observed on lunar regolith (e.g., Brownlee et al., 1973; Schneider et al., 1973; Fechtig et al., 1974; Morrison and Zinner, 1977; Morrison and Clanton, 1979), as well as on the meteoritic regolith breccias Kapoeta (howardite; Brownlee and Rajan, 1973) and Murchison (CM2 chondrite; Goswami et al., 1976). Therefore, understanding submicrometer-sized cratering processes on Itokawa particles can contribute to a general interpretation of small-scale impacting processes on airless bodies.

Previous studies have reported that the abundance of submicrometer craters on Itokawa particles is very low compared with similar features on lunar regolith; detailed surface observations identified only 24 submicrometer craters on 32 Itokawa particles with sizes from 20 µm to 50 µm (Nakamura et al., 2012; Harries et al., 2016; Matsumoto et al., 2016). Nakamura et al. (2012) suggested that submicrometer craters can be formed through direct impacts of nanometer-sized interplanetary dust particles. In contrast, the submicrometer craters found on Itokawa particles may have formed through impacts of secondary ejecta created by primary impacts on Itokawa, because submicrometer craters appear to be concentrated on only a limited number of specific Itokawa particles (Harries et al., 2016; Matsumoto et al., 2016). So far, statistical analysis of these craters has been limited because of the low crater abundances observed. Therefore, it is not clear whether the few observed craters represent the whole evolutionary picture of submicrometer cratering processes on Itokawa. In addition, the detailed abundances and production rates of submicrometer caters are not understood.

At the Extraterrestrial Sample Curation Center of the Japan Aerospace Exploration Agency (JAXA), Itokawa particles with an average diameter of 30 µm were retrieved from a sample catcher in the Hayabusa sample container (Yada et al., 2014). Thus far, surface features of Itokawa particles larger than 100 µm have never been examined in detail. These large Itokawa particles have large surface areas and they are the most suitable particles for extensive investigations of impact craters. The objective of the present work is to reveal accurate abundances of submicrometer craters and determine whether secondary impacts are representative agents driving the small-scale cratering processes on Itokawa. In the present study, we performed surface observations of 51 Itokawa particles ranging in size from approximately 15 µm to 240 µm and obtained unprecedented information on the areal distributions and morphologies of the craters on Itokawa particles. We report approximately 900 craters on Itokawa particles and compare the crater population with the flux of interplanetary dust particles and the lunar dust environment.

2. Observations

2.1. Samples

The Itokawa particles investigated in this study are listed in Table 1. The listed particles were collected from rooms A and B of a sample catcher, captured during the second and first touchdowns in the MUSES-C Region of Itokawa, respectively (Yada et al., 2014). The particles from room A (ID: RA-QD02-XXXX) were retrieved from a pure quartz disk after gently tapping on the exterior of the sample catcher, causing particles to drop onto the pure quartz disk (Yada et al., 2014). The particles from room B (ID: RB-CV-XXXX) analyzed in the present study were retrieved from the cover of room B (Yada et al., 2014). We examined 29 particles from room A (average diameters 24–240 µm) and 22 particles from Room B (average diameters 15–50 µm). The mineral phases and average diameters of the Itokawa particles (Table 1) were investigated based on their initial description (the detailed database is available at http://hayabusaao.isas.jaxa.jp/curation/hayabusa/index.html).

2.2. Observational procedure

Itokawa particles retrieved from the quartz disk and cover of room B were first analyzed with the field emission scanning electron microscope (FE-SEM; Hitachi SU6600) at the JAXA curation center to enable an initial description and preliminary identification of particle size and major mineral phases (Yada et al., 2014). The particles were placed on a gold-coated holder using an electrostatically controlled micromanipulation system.

In this study, we observed the surface morphologies of Itokawa particles using the FE-SEM after the routine initial description procedure. The particles were observed without conductive coating. As described by Yada et al. (2014), Itokawa particles observed in this study have never been exposed to an atmospheric environment, thus suppressing contamination and alteration of the particles. We performed secondary electron (SE) image observation at accelerating voltages of 1.5 kV and/or 2 kV in high vacuum with an electron beam current of approximately 10 pA. To assess their surface concavity or convexity, Itokawa particles were imaged from two angles, with a difference in tilt of 5°, to create stereograms. The particle surfaces were scanned initially at magnifications of 2000–10,000 in order to identify the presence of craters. Surfaces containing craters were re-examined at magnifications of up to 150,000.

One crater-rich Itokawa particle (RA-QD02-0275) was allocated for further research as part of JAXA's quota. The particle was adhered onto a carbon-conductive tape to secure sufficient electrical conduction for SEM analysis. This sample handling procedure was performed in a nitrogen-filled glove box at the JAXA curation center. Next, we transferred the particle to the Institute for Molecular Science (IMS, Higashi-okazaki, Japan). The particle was stored in a vacuum desiccator during transportation. We determined the elemental composition of its surface through energy-dispersive X-ray spectroscopy (EDS) using an FE-SEM (Hitachi SU6600) equipped with a Bluker XFlash® FlatQUAD detector at the IMS. The accelerating voltage for SE imaging was 1.5 kV, while for EDS analysis we used 5 kV and 10 kV.

3. Results

3.1. Spatial crater distribution

We identified numerous submicrometer-sized craters (Figs. 1 and 2) on 13 of the 29 Itokawa particles from room A (Fig. 3). On the other hand, we did not identify craters on Itokawa particles obtained from the cover of room B. The size distribution of