

“SPACE EROSION”: A NEW TYPE OF SPACE WEATHERING PROCESS ON THE SURFACE OF ASTEROID ITOKAWA. A. Tsuchiyama¹, T. Matsumoto² and T. Noguchi³, ¹Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University, Kitashirakawaoiwakecho, Sakyo-ku, Kyoto, 606-8502 Japan (atsuchi@kueps.kyoto-u.ac.jp), ²Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka, 560-0043 Japan (matsumoto@astroboy.ess.sci.osaka-u.ac.jp), ³The College of Science at Ibaraki University, 2-1-1 Bunkyo-cho, Mito, 310-8512 Japan (tngc@mx.ibaraki.ac.jp).

Introduction: Preliminary examination of regolith particles recovered from the surface of asteroid Itokawa by the Hayabusa spacecraft elucidated a variety of processes on the asteroid surface [1-10]. X-ray micro-tomography gave information on the three-dimensional (3D) shapes and surface morphologies of forty-eight Itokawa particles (~30-180 μm) [1-3]. The shape (three-axial ratios) distribution indicates that the particles are consistent with mechanical fragments by impact. ~75% of the particles have sharp edges while rest of them have rounded edges at least on a part of the particle surface, suggesting that mechanical fragments have been abraded. The abrasion process is possibly occurred due to particle motion by impact-induced seismic waves and/or sputtering by solar wind irradiation [1].

TEM and STEM observation on cross sections across the surfaces of twelve Itokawa particles found surface modifications by space weathering, which are responsible for change in reflection spectrum on the asteroid [4]. These space weathering rims are divided into three types [5,6]: Type-1: thin amorphous rims, Type-2: nanoblob-bearing rims, and Type-3: nanoblob-bearing vesicular (blistering) rims. The rim thickness and thus the degree of space weathering increases from Types-1 to -3. The blisters should be made by nucleation and growth of implanted high-energy particles, such as solar wind. The depth where blisters concentrate (~80 nm) corresponds to the penetration depth of solar wind He, which has typical energy of 4 keV. Thus, the space weathering rim formation is considered to be mainly caused by the solar wind He implantation.

Implantation of solar wind noble gases was detected by noble gas isotopic measurements of three Itokawa particles [5]. The time scale required for solar Ne exposure into the particles is 150-550 years. The upper limit of the residence time of the particles in the regolith layer estimated from cosmic-ray exposure is ~8 Myr. Release profiles of the noble gases by multi-stage laser heating indicate multiple implantations of solar wind particles, which are consistent with particle motion on Itokawa's surface.

Surface morphologies of eight particles were examined by a field emission scanning microscope (FE-SEM) [6]. Two types of surfaces were recognized. One has sharp fine steps, which mainly correspond to cleavage steps on fractured surfaces and sometimes

growth (or evaporation) steps in void walls. The other has faint structures such as ambiguous steps or rounded nano-edges without any steps. The former and later types of surfaces can be regarded as “fresh” and “matured” surfaces, respectively. Spotted structures due to blisters were also observed [9]. Micron-scale glassy objects that look like melt splash as a result of micro-meteorite impact were observed [8,10] although large-scale impact melting textures were not observed [1].

In the previous study, individual surface features have been independently discussed from their results. However, comparative examination especially on the same sample has not yet been made. In the present study, comprehensive approach for understanding processes on Itokawa's surface was made by comparing the results of different analyses. We made 3D models of plaster for the examined Itokawa particles (~5 cm in size) using their 3D shape data by micro-tomography. This enables us to easily compare surface features obtained by different methods in detail on specific areas of the same particle surfaces.

Comparison between surface micro- and nano-morphologies and rim nano-structure: Two kinds of surface morphologies with different spatial resolutions were examined. One is 3D morphology observed by the micro-tomography with the resolution of >a few μm [1-3] (hereafter we call this “surface micro-morphology”). The other is observed by FE-SEM with the resolution of >a few tens nm [8,9], (hereafter we call this “surface nano-morphology”). Eight Itokawa particles were commonly observed by these two methods. The particles are usually heterogeneous with respect to the surface morphologies. There is good correlation between the angularity of edges in the micro-morphology and the sharpness of steps in the nano-morphology when we compared on the same surface areas. Spotted structures due to blisters and melt splashes were observed both types of surfaces with angular and rounded edges in the micro-morphology or sharp and faint steps (or no steps) in the nano-morphology.

Space weathering rims observed by TEM and STEM have the spatial resolution of a few nm [4-6] (hereafter we call this “rim nano-structure”). Only one particle observed by micro-tomography, FE-SEM and

TEM/STEM has most evolved Type-3 rim on the surface with rounded edges without steps and with spotted structures. Seven particles were observed by micro-tomography and TEM/STEM but not by FE-SEM. There seems to be no correlation between the surface micro-morphology and the rim nano-structure although some of them were not directly compared on the same surface areas. However, it is clear that Type-3 rims were observed both on angular surfaces of two particles and a rounded surface of one particle.

We cannot compare the noble gas data with the surface morphologies and the rim structures because the destructive noble gas isotope measurements [7] were made without any observation by micro-tomography and FE-SEM to minimize contamination from the Earth's atmosphere.

Discussion: There is correlation between the surface micro- and nano-morphologies. It is reasonable to consider that "matured" particles with rounded edges and ambiguous steps (or no steps) were formed by abrasion from "fresh" fragmental particles with angular edges and sharp steps. However, there seems to be no correlation between the surface micro-morphology and the rim structures. In particular, Type-3 rims (nanoblob-bearing vesicular rims) were observed both on rounded and angular surfaces. Spotted structures due to blisters were also observed on the both surface types. Therefore, this most weathered Type-3 rim should form before the surface was deeply abraded. In fact, the time scale for the formation of Type-3 rims is relatively small: $\sim 10^3$ yr. based on solar flare track density observed by TEM in a particle with Type-3 rim [6] and between 500 and 5000 yr. based on the blister formation by high-energy He^+ implantation experiments [9]. The solar wind irradiation time scale based on the noble gas isotope measurements (150-550 yr.) [7] is also consistent with the short time scale [6].

As discussed above, the abrasion process has longer time scale than the space weathering rim formation, which is mainly caused by solar wind implantation. Thus, this abrasion process can be regarded as a different type of space weathering in a broad sense and is called "space erosion" here. The space erosion might occur by (a) particle motion due to seismic waves induced by small body impact, (b) sputtering by solar wind particles (possibly proton with typical energy of 1 keV) and (c) sputtering by micrometeoroid bombardments. The process (b) may be effective for modifying the surface nano-morphologies but probably not for the surface micro-morphologies. The process (c) may not be effective on relatively young Itokawa's surface ($\sim 8 \times 10^6$ yr.) [6]. In addition, both processes of (b) and (c) can occur only when particles were situated at Itokawa's uppermost surface. Therefore, the process (a) might be plausible although the abrasion rate by this process is unknown.

Whatever the causes for the space weathering processes, there are the two kinds of space weathering process on Itokawa's surface: one is the formation of space weathered rim (so-called "space weathering", which is responsible for the change of reflection spectrum) with a short time scale ($< \sim 10^3$ yr.) [4-6], and the other is space erosion with a longer time scale ($< \sim 10^7$ yr.). Regolith particles recovered by the Hayabusa spacecraft have been evolved on Itokawa's surface probably by the following processes. (1) Formation of fine particles (~ 100 μm in size) by impact of small bodies onto Itokawa. A small amount of fine particles that have relatively low velocities could survive although most of them escaped from Itokawa [1,7]. (2) Formation of space weathering rims from Types-1 to -3 mainly by solar wind implantation for $\sim 10^3$ yr if the particle surfaces were exposed to environment on Itokawa's uppermost surface. (3) Space erosion probably due to seismic-induced particle motion in a regolith layer for sufficiently longer duration than $\sim 10^3$ yr. The processes (2) and (3) might be repeated by the particle motion during stay in a regolith layer ($< \sim 8$ Myr.). Abrasion of space weathering rims by the particle motion might effectively occur. Some particles might be formed in a rough terrain of Itokawa's surface and eroded during transportation to the smooth terrain [11].

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