ABRASION EXPERIMENTS OF MINERAL AND METEORITE GRAINS; APPLICATION TO SHAPE EVOLUTION OF REGOLITH PARTICLES ON AIRLESS BODIES.

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Introduction: The shape of regolith particles in airless bodies has information about processes on their surfaces. 3D shapes of Itokawa (~15-150 μm) [1-3] and lunar regolith particles (~30-450 μm) [4-6] have been examined using X-ray microtomography. 3D shapes of fine impact-experiment fragments (<~120 μm) have been also examined and it was found that the mean 3-axial ratio, L:I:S ($L \geq I \geq S$), is ~1:1/√2:1/2 in a wide range of impact conditions (from cratering to catastrophic disruption) [7]. The mean 3-axial ratio of the Itokawa particles is close to 1:1/√2:1/2 [7] confirming that Itokawa particles are impact fragments on the asteroid surface. In contrast, lunar regolith particles are more equant than the impact-experiment fragments irrespective of their localities (highland and mare), maturities and size ranges [4-6] although the lunar particles should be also formed by impact.

The external 3D shapes and surface nano-micromorphologies of Itokawa and lunar particles by X-ray microtomography and SEM showed that some particles have rounded edges, which should be formed by mechanical abrasion [1,8,9]. On the Itokawa surface, seismic wave induced by micrometeoroid impacts [1], YORP effect and tidal motion [10] were proposed for the abrasion process. In this study, we made abrasion experiments in order to understand detailed abrasion processes and to apply the results to evolution of regolith particles on the airless bodies.

Experiments: We used quartz, olivine (Fo$_{\sim 90}$ from San Carlos), corundum and calcite (marble) as mineral samples and Sayh al Uhaymir 001 (L5) and Marchison (CM2) as meteorite samples (Table 1). The samples were crushed and particles 1-2 mm in size were selected except for corundum (~1mm). These particles (~6.5g) were put into a vessel (10 mL), which corresponds to the sample material, with ~50% fraction without any crushing tool. Then the vessel was rotated with the vertically-vibrational motion in a mill (Multi-beads-shocker: YASUIKIKAI Co.).

Two types of experiments were performed. In Type-1 experiments, six marked grains were added to the sample grains to trace their 3D shape changes by abrasion (Table 1). Three kinds of tracer grains were used; (1) colored quartz added in colorless quartz grains, (2) L5 added in olivine grains (simulate for Itokawa particles) and (3) CM2 added in marble grains (simulate for Ryugu and Bennu particles in Hayabusa-2 and OSIRIS-REx missions). Olivine and marble grains were selected because of their similar strengths to the meteorite samplers. The samples were rotated at a rotation rate, ω, from 1000 to 2500 rpm for accumulated durations from 1 to 180 min. After each abrasion cycle, the tracer grains were picked up and their 3D shapes were imaged using X-ray microtomography at BL20B2 of SPring-8 (25keV, pixel size: 2.75 μm). The particles were returned to the vessel, and abrasion cycles were repeated. The mass of powder (<250 μm) produced by abrasion was measured at each abrasion cycle.

Table 1 Experimental conditions.

Type-1	tracer	vessel	rotatin rate (rpm)	accumulated duration (min)	powder
quartz	quartz*	agate	1500, 2500	1, 5, 10, 30, 60, 120, (180**)	removed at each cycle
quartz	quartz*	agate	1500, 2000, 2500	1, 5, 10, 30, 60, 120, 180	returned at each cycle
olivine	L5	dunite	1500, 2000, 2500	1, 5, 10, 30, 60, 120, 180	returned at each cycle
marble	CM2	limestone	1000, 1500, 2000	1, 5, 10, 30, 60, 120, 180	returned at each cycle
Type-2		vessel	rotatin rate (rpm)	duration (min)	
quartz		agate	1500, 2500	1, 5, 10, 30, 60, 120, 180 ,720	
quartz		agate	1000, 3000	1	
olivine		dunite	1000, 3000	1	
corundum		corundum	1000, 1500, 2000, 2500, 3000	1	

* amethyst, citrine and morion; ** only at 1500 rpm

In Type-2 experiments, quartz grains were rotated at a rate of 1500 or 2500 rpm for durations from 1 to 720 min (Table 1). In each run, the mass of powder (<250 μm) produced by abrasion was measured. More than 150 particles randomly sampled were imaged by X-ray tomography at Tohoku University (140 keV, pixel size: 14.5 μm) to obtain their 3D shapes. The powder masses of minerals produced for the first 1 min at different ω's were also obtained to compare the abrasion rates.

Results: The powder mass increases with increasing duration at a constant ω but the rate decreases. Powder mass produced for the first 1 min normalized by the initial mass, Δm_1, is plotted against ω for different samples (Fig. 1). Δm_1, increases with ω in a power law with the power index of ~2 to 3. The abrasion rate increases from corundum, olivine~quartz to calcite, and this order is consistent with their mechanical strengths.

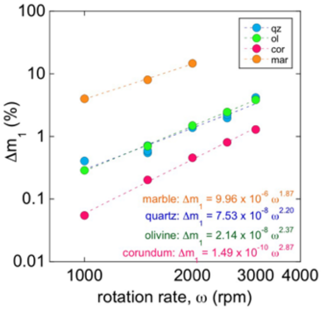

Figure 1. Powder mass produced for the first 1 min normalized by the initial mass, Δm_1, plotted against rotation rate, ω.

In Type-1 experiments, tracer grains became rounded by abrasion. Abrasion of quartz grains proceeded mainly by gradual wearing at low ω (1500 rpm) while by chipping particle edges as well as gradual wearing at high ω (2000 and 2500 rpm) (Fig. 2). For the meteorite grains, breaking along pre-existing cracks and plucking of objects also occurred.

The volume of a tracer grain decreases and the angularity (approximated ellipsoid volume/particle volume) and sphericity (approximated ellipsoid surface area/particle surface area) generally become unity (non-angular or spherical) with increasing duration particularly for the first 1 min but the rates are different grain-by-grain. The volume change is generally larger for larger ω.

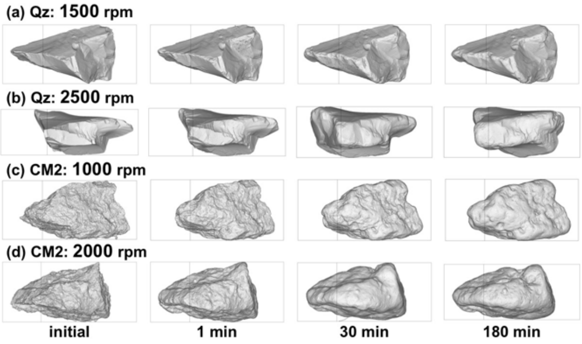

Figure 2. Change in quartz and CM2 grain shapes.

The 3-axial ratio almost unchanged by abrasion at low ω (e.g., 1500 rpm for quartz and 1000 rpm for CM2) while changed at large ω (e.g., 2000 and 2500 rpm for quartz and 1500 and 2000 rpm for CM2). However, the shape changes to different direction depending on its original shape and not to an equant shape (Fig.3). In Type-2 experiments, the mean 3-axial ratio changed to an equant shape particularly at 2500 rpm (Fig. 4).

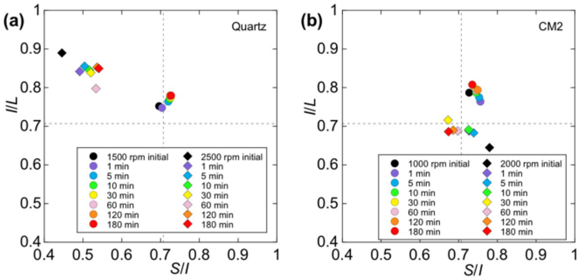

Figure 3. Change in the mean 3-axial ratio of individual grains in Type-1 experiments. (a) Quartz grains of Figs. 2a and b. (b) CM2 grains of Figs. 2c and d.

Discussion: The mode of abrasion (Fig. 2) and the 3-axial ratio change (Fig. 3) of the tracer grains show that the 3-axial ratio unchanged by gradual wearing but changed by chipping and/or breaking. Shape change of individual grain by chipping occurs in intense abrasion depending on its original shape while overall the mean 3-axial ratio becomes equant (Fig. 4). Stochastic change in the volume, angularity and sphericity of individual grain can be also explained by this model.

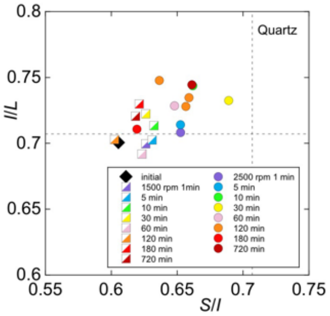

Figure 4. Change in the mean 3-axial ratio of quartz grains by abrasion in Type-2 experiments.

The present experimental results showed that rounded edges of Itokawa and lunar regolith particles were formed by gradual wearing in abrasion. The mean 3-axial ratio of Itokawa particles of ~1:1/$\sqrt{2}$:1/2 can be explained by gentle abrasion without chipping. This is consistent with granular motion on Itokawa by impact-induce seismic wave [1] or YORP effect [10]. Breaking along cracks might also occur as indicated by Type-1 experiments using the meteorite grains. This can explain coexistence of rounded edges and fractured surfaces on some Itokawa particles [8].

In contrast, lunar particle shapes can be explained by intense abrasion with chipping as well as gradual wearing. If impact occurred onto a regolith layer, regolith particles became equant by intense abrasion in a fluidal particle flow. In this case, particle fragmentation by impact itself also occurred as well as breaking along cracks. By repeated impact events, the shapes did not become largely spherical but the mean 3-axial ratios were saturated in intermediate values.

It should be noted that the grain size used in the present experiments (~1 mm) is larger than the regolith particle size (~0.1 mm). Similar abrasion process (gradual wearing and chipping) may occur for smaller particles although the size effect is not known. In addition, the size of grains formed by chipping in the present experiments (~0.1 mm) is comparable with the regolith particle size. This may indicate that at least some of fine regolith particles were formed by chipping during abrasion particularly on Moon.

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