PHYSICAL PROPERTIES OF SILICATE-RICH REGOLITH PARTICLES FROM ITOKAWA ASTEROID

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Introduction: The Hayabusa spacecraft rendez-voused with asteroid 25143 Itokawa in 2005 and brought regolith samples, collected during two touchdowns carried out on 19 and 25 November 2005 in its smooth terrain (MUSES-C), and returned to Earth in a sample-return capsule in 2010 [1]. The Itokawa reflectance spectrum corresponds to that of S-type asteroids, and its bulk mineralogy is consistent with the LL group of ordinary chondrites [2]. The surface of Itokawa consists of non-uniformly distributed boulders and regolith [3]. Cratering structures on Itokawa of meter- to hundred-meter sizes have been identified [3]. Evidence of a re-arrangement of boulders and migration of regolith, possibly owing to impact or tidal shaking, has also been identified on Itokawa [3-4]. Here we concentrate in studying the mechanical and magnetic properties of three regolith particles returned by Hayabusa mission using the nano-indentation technique. Our methodology, first applied to meteorites in a previous work [5], could be used in a next future to study the properties of Ryugu materials to be returned by Hayabusa 2.

Technical Procedure: Three Itokawa particles provided by JAXA, embedded in epoxy resine and polished to mirror-like appearance, with numbers RA-QD02-0014, RA-QD02-0023 and RA-QD02-0047 (hereafter designated as S14, S23 and S47 for simplicity) were investigated. First three samples were analyzed by optical microscopy and scanning electron microscopy (SEM). A scanning electron microscope FEI Quanta 650 FEG is working in a low-vacuum BSED mode. An EDX Inca 250 SSD XMax20 detector with an active area of 20 mm^2 is applied for elemental analysis of the samples. Micro-Raman spectra with a spot size of approximately 1 µm and laser power below 0.6 mW were obtained in order to study the shock experienced by the samples and give us chemical and structural information of different phases. Backscatter measurements were done at room temperature using the 5145 Å line of an Argon-ion laser with a Jobin-Yvon T-64000 Raman spectrometer attached to an Olympus microscope which equipped with a liquid nitrogen–cooled CCD detector. The Raman spectrometer is working in windows between 100 and 1400 cm^{-1} to acquire high resolution spectra.

The mechanical properties (hardness and reduced Young's modulus) were evaluated by the method that Oliver and Pharr (1992) first used. We choose the maximum applied forces of 5 mN and 10 mN in order to keep the maximum penetration depth below one fifth of the overall thickness of the sample. We applied some necessary corrections for the contact region and adoption of the instrument. We also kept the thermal drift below 0.05 nm·s^{-1}. The contact stiffness, was defined as:

$$S = dP/dh \tag{1}$$

P denotes the applied load and h means the penetration depth during nanoindentation. P_{max} is the maximum load applied in the surface area A. Hence Hardness was calculated from the following equation:

$$S = \frac{P_{max}}{A} \tag{2}$$

The elastic recovery calculated as the ratio between the elastic energy, U_{el} -estimated from the area between the unloading indentation segment and the x-axis- and U_{tot} (U_{el}+U_{pl}, where U_{pl} is the plastic energy)- estimated as the area between the loading indentation segment and the x-axis.

We also determined the reduced Young's modulus, E_r, defined as:

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i} \tag{3}$$

The elastic displacements occur in all three samples, with Young's modulus E and Poisson's ratio ν, and the indenter, with elastic constants E_i and υ_i. Representative nanoindentation curves for one of the studied particles are shown in Fig. 1, from which the mean mechanical properties resulted from the analyzed region, can be extracted (Table 1).

As the hardness values are not remarkably different at 5 and 10 mN, it seems that the hardness has not affected by amount of the indentation load. It means that with our chosen loads, the strain-hardening phenomena that could happen due to the indentation size effect was avoided.

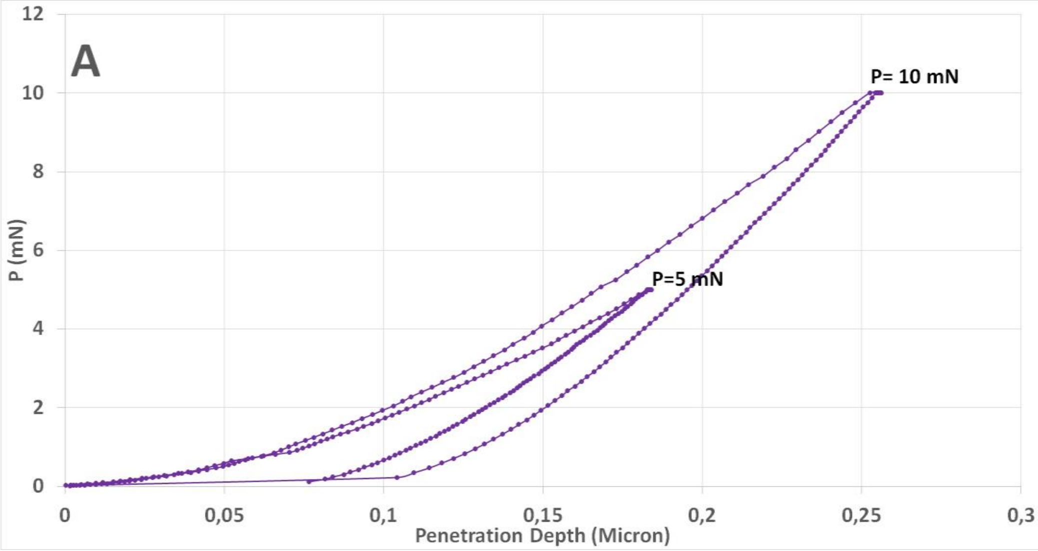

Figure 1. Indentation curve obtained for S14 sample.

Table 1. Average mechanical properties for three silicate-rich regolith particles of asteroid Itokawa. Reduced Young's modulus (E_r), hardness (H), constant stiffness (S), elastic recovery (U_{el}/U_{tot}) and plasticity index (U_{pl}/U_{tot}) were calculated by averaging the results from two lines of indentations from the maximum applied force of 5 mN.

E_r (GPa)	H (GPa)	S (mN/ micron)	U_{el}/U_{tot}	U_{pl}/U_{tot}
93.0 ± 0.20	10.33 ± 0.03	77.0 ± 0.20	0.75 ± 0.07	0.25 ± 0.07

Conclusions: Itokawa regolith is made of fractured particles produced by the collisional gardening of its surface along the eons. Their forming silicates are shocked, annealed and chemically homogenized, as we have also demonstrated using Raman spectroscopy [4]. This is consistent with regolith particles created by disaggregation, primarily as a response to impacts, but thermal fatigue cannot be ruled out in some cases [5]. In general, the mechanical properties of Itokawa regolith particles are comparable with silicates forming LL chondrites like e.g. Chelyabinsk. In any case, the elastic recovery of Chelyabinsk meteorite minerals exhibit lower values than these measured for Itokawa regolith grains. Despite of the homogeneous composition, we have discovered that some particles have distinctive areas that have been preferentially shocked. The induced drift in the positions of the olivine Raman peaks is due to changes in the olivine structure, typically associated with a structural rearrangement of the lattice. On the other hand, the reduced Young's modulus values obtained here for the Itokawa meteorite are above the measured for Chelyabinsk meteorite [6]. There is difference in the Young's modulus but hardness values are similar. Concerning the magnetic properties, we have found a soft magnetic behavior with a coercivity of around 70 Oe. The observed magnetic properties are consistent with the presence of tiny Fe and Ni inclusions in the samples, as was detected by energy-dispersive X-ray (EDX) analyses, leading to the formation of FeNi, FeO or FeS_2, among others.

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