MECHANICAL PROPERTIES OF SILICATE-RICH ITOKAWA REGOLITH PARTICLES.

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Introduction: The Hayabusa spacecraft rendezvoused 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]. These features suggest that the materials on Itokawa's surface are still moving; the changes in position of boulders and regolith are correlated with the observed color variation [3] suggesting that the degree of space weathering depends on the surface region.

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 microto nanometer scales. The recovered regolith samples provide micro- to nanometer-scale information about the formation process of fine regolith, importance of thermal annealing, and chemical homogenization by collisional gardening of Itokawa's surface [4]. Here we concentrate in studying the mechanical properties of three regolith particles returned by Hayabusa mission.

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 (which will be designated as S14, S23 and S47 for simplicity from now on) were received at ICE. They were analyzed by SEM/EDX before being nanoindented, using a filter of 50 nm. ESX is a technique allowing quick semi-quatitative identification and characterization of mineral phases in chondrules. Microprobe analysis are required for accurate quantitative analyses of the bulk mineral composition in order to characterize meteorites [5].

Two arrays of indentations were performed on each sample in the load control mode, applying maximum forces of 5 mN, using an UMIS equipment from Fischer-Cripps Laboratories equipped with a Berkovich pyramidal-shaped diamond tip. The distance between two consecutive indents was chosen to be 5 μm, so as to avoid any interfence of the induced stress fields between neighboring indentation experiments.

Results and Discussion: The mechanical properties (hardness and reduced Young's modulus) were evaluated by using the method of Oliver and Pharr. The values of maximum applied forces were chosen to be 5 mN to ensure that the maximum penetration depth during the tests was kept below one fifth of the overall film thickness, hence minimizing influence from the resine. The thermal drift during nanoindentation was kept below 0.05 nm.s^{-1}. Proper corrections for the contact area, instrument compliance, and initial penetration depth were applied [6]. The *contact stiffness*, was determined as:

$$S = dP/dh \qquad (1)$$

Where P and h denote, respectively, the applied load and the penetration depth during nanoindentation. *Hardness* was calculated from the following expression:

$$S = \frac{P_{max}}{A} \qquad (2)$$

Where P_{max} is the maximum load applied during nanoindentation. Finally, the elastic recovery was evaluated as the ratio between the elastic and the total (plastic/elastic) energies during nanoindentation, U_{el}/U_{tot}. U_{el} was determined as the are between the unloading indentation segment and the x-axis, while U_{tot} (equal to $U_{el}+U_{pl}$) was the area enclosed between the loading indentation segment and the x-axis.

E_r is the so-called *reduced Young's modulus*,

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\upsilon_i^2}{E_i} \qquad (3)$$

The reduced modulus takes into account the elastic displacements that occur in both the specimen, with Young's modulus E and Poisson's ratio *nu*, and the indenter, with elastic constants E_i and υ_i [7]. Representative nanoindentation curves for S14 particle are shown in Fig. 1, from which the mean mechanical properties obtained from the the region analyzed can be extracted (Table 1).

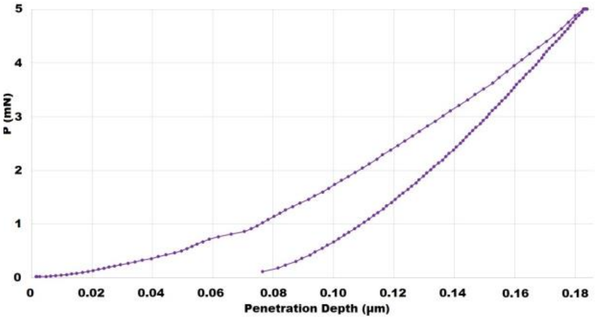

Figure 1. Indentation curve obtained for S14 sample.

Table 1. Average mechanical properties of Itokawa regolith silicates in particles of given number S#. Reduced Young's modulus (E_r), hardness (H), elastic recovery (U_{el}/U_{tot}) and plasticity index (U_{pl}/U_{tot}) were calculated averaging the results obtained from two lines of indentations.

S#	Er (GPa)	H (GPa)	S (mN/ micron)	$U_{el}/$ U_{tot} (nJ)	$U_{pl}/$ U_{tot} (nJ)
14	83.01 ± 0.12	8.012 ± 0.005	77.01 ± 0.11	0.6456 ± 0.0003	0.3678 ± 0.0003
23	111.01 ± 0.22	10.01 ± 0.02	92.0 ± 0.2	0.73 ± 0.07	0.27 ± 0.07
47	86.01 ± 0.13	13.01 ± 0.03	62.01 ± 0.03	0.878 ± 0.001	0.1345 ± 0.0001

Conclusions: Most Itokawa regolith particles have more or less fractured structure, and are probably comminuted from larger chondrules. Their forming silicates seem to be partially annealed and chemically homogenized. This is consistent with the proposal that Itokawa particles were formed by disaggregation, primarily as a response to impacts, although we cannot exclude the possibility that the regolith particles were formed by thermal fatigue [4]. In general the mechanical properties of Itokawa regolith particles are comparable with silicates forming Chelyabinsk. The elastic recovery of minerals of Cheyabinsk represents values lower than Itokawa samples.

The reduced Young's modulus values obtained here for the Itokawa meteorite are above the Young's modulus measured previously for Chelyabinsk meteorite, between 69 and 78 GPa [8]. There is difference in the Young's modulus but hardness values are similar.

Acknowledgements: This study was supported by the Spanish grant AYA 2015-67175-P, and ST made this study in the frame of a PhD. on Physics at the Autonomous University of Barcelona (UAB). We also thank Dr. Toru Yada and the Hayabusa curation staff of JAXA for providing the samples analyzed here.

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