MEASUREMENTS OF ADHESION VALUES OF METEORITE MATERIALS AND THEIR APPLICATIONS TO ASTEROIDS.

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Introduction: Many mysteries about asteroids could be better understood if there was a more precise estimate for the adhesive forces of the regolith, or surface material, of an asteroid. Adhesion – the degree to which particles of a material will stick together – is a relevant factor not only for missions to asteroids, but also for understanding how asteroids form and change over time. It is accepted that smaller, unconsolidated “rubble pile” asteroids are held together largely due to these adhesive forces [1]. For some of these bodies, their minimal gravity alone should be insufficient to keep them together, especially if they have a high rotational period [2, 3].

Current assumptions of adhesion values are estimates based on lunar or terrestrial analogs [4]. There are notable disctinctions between these and asteroids, such as the inclusion of ductile metals and hydrated phases [5]. This results in a large range of estimated values with an associated large margin of error.

While studying asteroid materials in-situ would be ideal, that option is not currently available. Instead we can look to meteorites as a source of information, given the strong evidence that asteroids are their parent bodies. Their compositions can include a wide range of minerals, and thus meteorites are categorized into distinct types. For our experiments, measurements of adhesion were taken for a CM2 carbonaceous chondrite (LON 94101) and several of the dominant minerals associated with the CM2. We chose this class because it is thought to represent C class asteroids. This is the most common class and the focus of several upcoming missions including ARM, Hayabusa2, and OSIRIS-REx [4, 6]. The mineral abundances for LON 94101 were obtained through SEM based elemental mapping and X-ray diffraction, which showed mixed phyllosilicates to be the most abundant phase (accounting for 91% of the sample), followed by pyroxenes, olivine, metal, and carbonates [7]. The goal of our experiment was to obtain a realistic measurement of adhesion forces within CM materials, reflecting the heterogeneity inherent in these meteorites (and their parent asteroids).

Methods: Samples representative of the major minerals were first properly characterized and were machined into the necessary shapes for use in adhesion testing. The CM2 was cut into a thin 10 mm square plate, and each of the minerals were made into ~3 mm diameter pins. The pins had roughly hemispherical tips to minimize surface area in contact with the plate.

The “Adhesion Rig” is a unique device developed at NASA Glenn. The system features an ultra high vacuum chamber, allowing for adhesion measurements to be obtained at pressures on the scale of 10^{-10} torr. The system is also able to perform Auger Electron Spectroscopy and ion cleaning on samples inside the chamber.

The plate of CM2 was mounted on a small torsion balance inside of the chamber, with displacement sensors across the bar. The bar was suspended on a taught wire. A pin sample made from one of the minerals was mounted on the end of a rod which could move in X, Y, Z, and rotational directions. The plate hung sideways so that gravity would not influence the measurements. Before each day of testing, samples were ion cleaned to remove contamination or carbon build up.

Figure 1: Set of pins used in the adhesion testing.

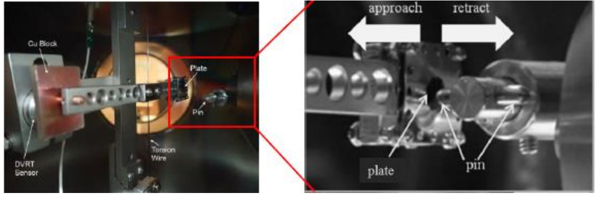

Figure 2: A view inside the chamber of the entire balance and sensors (left), and close up of the pin and plate making contact (right).

Measurements were collected by using the apparatus to move the pin and push it into the plate. Loading the plate causes the bar to twist around the wire, and the spring force of the wire will resist. Using the spring constant of the wire, the applied force can be calculated. After the pin and plate had been left in contact for a desired amount of time, the pin was then retracted. If any adhesion occurred, the plate would continue to move with the pin past its equilibrium point before returning to its initial position

The Rig has been used previously in adhesion research [8], though the materials used were homogeneous, such as a synthetic volcanic glass. A major challenge of our research is in using nonhomogenous natural materials, many of which are difficult to machine. An original goal was to test a CM2 plate on a CM2 pin, but the material was too difficult to form into the proper shape for a pin. Instead we used analogous minerals as pins. The individual minerals used in this experiment include bronzite (an Mg-Fe bearing pyroxene), iron nickel (FeNi) metal, olivine (Mg-Fe bearing silicate), serpentine (a brittle, platy Mg-Fe bearing phyllosilicate), and siderite (Fe bearing carbonate). The most difficult to choose was the analog for matrix material of the CM2, which contains minerals whose terrestrial equivalents are exceptionally rare (such as tochilinite and Fe-cronstedite). Serpentine served this role for our experiments. We then measured the adhesion of all these pins against our mixed-phase CM2 plate many times (~150x) and in multiple locations to reflect the overall heterogeneity.

Additional runs called "hammer strikes" were performed to check effects of tribocharging (a charge build up from touching of different surfaces). During these, the pin and plate would be positioned to be barely apart, then the chamber was lightly tapped with a rubber mallet, causing the pin to strike the plate, to try to induce tribocharging.

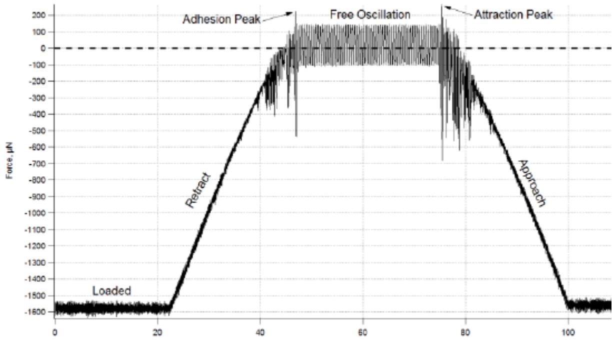

Figure 3: An example adhesion run, beginning with the plate and pin in contact. Pulling off results in an adhesion peak, where the pin and plate stuck. This run also shows an attraction peak at the start of the next approach; this is attributed to electrostatic charging. Force is plotted as a function of time. Forces are measured in µN. Data was collected using LabView and analysis done with IGOR.

Results: Because adhesion was seen irregularly (~12% of the time), a large number of runs (775 total, ~150 for each pin) were conducted and the data was analyzed statistically. In order to make the process more efficient, rather than manually identifying peaks, an automatic method was developed. The program identifed adhesion and attraction peaks that were 5 µN or greater than the free osciallation level for that run. This threshold was used for preliminary analysis, but may be refined as the data is investigated further.

As of this writing, it is clear that different minerals have different adhesive strengths. Serpentine exhibited the strongest and most frequent adhesion. Second strongest is siderite, though siderite only registered adhesion about half as frequently as serpentine. Ranking third is bronzite. Olivine and FeNi performed similarly and had the lowest degree of adhesion out of the minerals tested. Certain runs seemed to show a dependence on pin orientation – for example, during a series of serpentine tests, adhesion was more likely if the pin was at an upward angle. Profilometery of the pins and plate was performed, both before and after testing, but no conclusive features were found to explain why this may happen. Additionally, the amount of time the plate and pin are loaded and the distance the plate was pushed back didn't appear to affect adhesion.

Discussion/Conclusion: It is notable that serpentine is by far the most adhesive mineral studied. Serpentine is the most dominant mineral present in the CM2 sample, so in this case, it is "cohesion" rather than "adhesion". If serpentine is more likely to stick to itself than to other minerals, then meteorites (and asteroids) rich in serpentine and similar phyllosilicates could be rather cohesive. The "stickiness" of the serpentine likely relates to its crystal structure. As a phyllosilicate, serpentine can be brittle, platy, and fibrous, with realtively weak bonds between its sheet-like layers.

Attraction peaks must be caused by electrostatics, as Van der Waals forces do not act over a long enough distance to cause the attraction. The daily ion cleanings and hammer strike tests are sources for charging. It is likely that any adhesion seen in a run immediately following a hammer strike will be due to electrostatics, and some preliminary data suggests that the charge after a hammer strike takes around 5 minutes to dissipate. Subsequent touching of the pin and plate together a greater number of times may cause the charge to dissipate more rapidly. Van der Waals forces are the likely cause of adhesion on runs that have an adhesion peak but not an attraction peak, and occur long enough after an ion cleaning or hammer test. Based on the analysis so far, roughly 8% of the observed adhesion is likely attributable to Van der Waals, but more study is needed.

Future Work: Additional adhesion tests will be conducted in the coming months, featuring other minerals found in LON 94101 (such as troilite), and we have recently constructed a CM2 pin; experiments using this will be attempted. Our hope is that this test may provide the most realistic value of adhesion for C-class material available.

References: [1] Scheeres et al. (2010) *Icarus* 210, 968-984. [2] Rozitis et al. (2014) *Nature*, 512. [3] Polishook et al. (2016) *Icarus* 267, 243-254. [4] Mazanek et al. 2016, NASA. [5] McCoy et al. 2002 *Chemi der Erde-Geochemistry* 62.2: 89-121. [6] Libourel et al. 2014. *Elements* 10.1: 11-17. [7] Gaier et al. 2016, NASA. [8] Berkebile et al. 2012, NASA