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Towards the use of mushroom-capped dry adhesives in outer space: Effects of low pressure and temperature on adhesion strength

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ABSTRACT

Instrumented indentation apparatus and techniques were applied to the testing of synthetic gecko adhesives in an attempt to characterise their ability to function in a space environment. The indentation apparatus was capable of operating at reduced pressures, allowing a higher vacuum level (1×10^{-5} mbar) than dry adhesives have previously been tested under. Using a 1.5 mm spherical quartz indenter on polydimethylsiloxane (PDMS), mushroom-capped, structured dry adhesives, the effective Young's Modulus of the material was found to change negligibly as a result of pressure, while no changes in adhesion were observed. The effect of time spent in vacuum was also examined. Significant changes in effective Young's Modulus were observed, but no changes were noted in adhesion. Tests also showed that no significant changes to adhesion could be detected from −50 to 75 °C. These results are important for space applications because it shows that the adhesion of a mushroom-capped, synthetic, PDMS, dry adhesive is constant in various thermal and pressure environments.

1. Introduction

Synthetic, bio-inspired dry adhesives with mushroom caps have a number of properties that make them ideal for use in space environments such as adhering to the exterior of an orbiting spacecraft. They are passive and potentially reusable mechanisms that can adhere to a variety of surfaces unlike magnets (which need ferrous surfaces), Velcro™ (which needs a mating surface), spines (which need a rough surface) or suction (which requires a smooth surface and does not work in vacuum).

Synthetic dry adhesive tests can be conducted in two major ways: with a flat-on-flat probe (e.g., [2,5]) or a spherical probe (e.g., [3,4,7,8,11,12]). Typically the preload force is controlled (either directly with a force feedback controller or indirectly with a displacement controller) by moving a stage-mounted or cantilever-mounted probe to the sample. Most often the preload is represented as a force (e.g., [18]), but with some apparatus the probe displacement has been resolved and is used as the controlled variable (e.g., [4,12]). Examples of testing apparatus found in the literature include a microtribometer system [5], indenter system [4], load cell and stage system [6], and pivot balance [2]. Some tests conducted on dry adhesives include post geometry and contact shape [9,12], detachment speeds [1,5], indenter geometry [9], Young's Modulus [1], repeated measurements and time delays between measurements [7,8]. While gecko and gecko setae adhesion has been shown to depend on ambient humidity [13–15], humidity has been reported [3,17] to not affect adhesion of synthetic dry adhesives made from polydimethylsiloxane (PDMS). To the best of our knowledge, while temperature has been shown to have an effect on the adhesive ability of a live gecko [13], the effect of temperature on adhesion has not yet been quantified.

Models have been developed to explain the adhesive force resulting from a given preload. A cylindrical indenter was considered in [10], however few, if any, tests have been conducted on synthetic dry adhesives using such an indenter. In [12], the relationship between preload depth and contact area for a spherical indenter is used to compare contact areas across different samples. Considering each of the structured posts as springs results in the model in [18]. The model in [18] has also been used by [4] to explain their data, however they report some difficulty in fitting data to it because one of the model parameters has a power 4 dependence making the fit highly sensitive to this parameter.

Observing the effect of vacuum on adhesion gives an indication of whether dry adhesives with mushroom caps (which have the appearance of a miniature suction cup under high magnification [11]) are adhering using suction instead of (or in conjunction with) van der Waals forces. As suction cannot be supported in vacuum, the potential for a reduction of adhesion in vacuum has

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implications for space use of synthetic dry adhesives. One macro-scale test [11] found no effect of vacuum on adhesion, but the number of trials and confidence interval of the result was not stated. In [2] flat-on-flat measurements on the macro-scale were performed in vacuum, with an estimated effect of over 25%, however it appears their result was only based on only one measurement. Flat-on-flat measurements were also performed by [5] with a statistical analysis. An effect of vacuum was found at pulloff speeds faster than 400 $\mu m\,s^{-1}$. Using a hemispherical probe, [17] did not see an effect at low cap sizes, but saw a reduction of adhesion at large cap sizes which was attributed to cap failure instead of suction. To the authors' knowledge, the lowest pressure achieved in previous work at the time of this publication while testing dry adhesives was 10 mbar [11] with non-instrumented apparatus and 20 mbar [5] with instrumented apparatus.

In this research, a Nano-Scratch Tester (NST) was used to perform adhesion measurements with a spherical probe while recording both load and displacement values. With this apparatus it was feasible to test at lower pressures than in previous work and also at various temperatures. The tests were designed to demonstrate how synthetic dry adhesives would perform in a space environment. In this paper, first the research methods are outlined, including adhesive fabrication and a description of the testing apparatus. Next the results and discussion are presented, with models fit to the data where appropriate. Conclusions are drawn at the end of the manuscript.

2. Methods

Samples were fabricated by moulding PDMS using the method in [16], generating an adhesive area of approximately 7000 mm^2. For mounting in the testing apparatus, a 100 mm^2 section of adhesive was cut from the large adhesive area and attached to a copper block using a silicone compound (Bison, High Temp Silicone). Images of the adhesive from the side and top were taken with a Scanning Electron Microscope (SEM) and are given in Fig. 1. The adhesive posts were 10 μm tall with 17 μm diameter circular caps and were cast in a square array with side length 20 μm. The testing apparatus was an NST from CSM instruments mounted in a custom vacuum chamber, shown in Fig. 2. Roughing and diffusion pumps (Edwards) were connected to the system, which had an ultimate pressure of 1×10^{-5} mbar with the polydimethylsiloxane (PDMS) sample inside. Vibrations were dampened using an air table and compressor (Jun-Air), and a damping block (Edwards) on the roughing pump hose. The sample was mounted inside the chamber on a 3-axis positioner (Maxon). The probe was a 1.5 mm diameter quartz sphere with a maximum roughness of 0.22 μm, which was glued with cyanoacrylate to a 2 mm diameter steel pin. The NST cantilever holding the probe had a measurement resolution of 0.15 μN in load and 0.3 nm in depth. Displacement was measured with a Linear Variable Differential Transformer (LVDT) at the end of the cantilever and at a fixed reference attached to the chamber. The load was computed from the LVDT measurement and spring constant of the cantilever (0.6820 $mN\,\mu m^{-1}$). A microscope was mounted inside the chamber. The sample could be moved between the probe and the microscope for inspection.

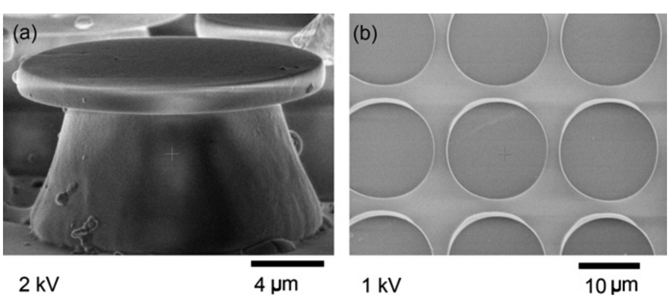

Fig. 1. SEM image of a single mushroom-capped dry adhesive post (a) and an array of adhesives from the top (b).

When testing in vacuum, the vacuum pumps were left on during testing to keep the pressure nearly constant. During pump down, under the microscope the sample was observed to move relative to the indenter. Motion in the x and y (planar) directions was estimated at 5 μm, and in the z direction (vertical) at 100 μm. The relative shift meant that testing the same sample location in both vacuum and atmosphere was not feasible. Pilot testing showed variability in adhesive force between locations on the adhesive sample. To reduce variability, a number of locations were tested.

Over 800 measurements were conducted at various locations on the adhesive and at various preloads within the operational range of the load sensor (about 12 mN of adhesion). These were taken at room temperature (27.1 °C), and at either atmospheric pressure or 1×10^{-5} mbar. To take each measurement, the cantilever was controlled in depth to indent to a specific preload depth, and then retracted until detachment. Data was sampled at 100 Hz and indentation depth, indentation force and adhesion force were obtained through post-processing. The result of a typical single measurement is plotted in Fig. 3a. In this measurement, a preload (compressive force) of 0.31 mN resulted in a detachment (tension force) of 5.5 mN. In Fig. 3b, a detailed view of the detach-

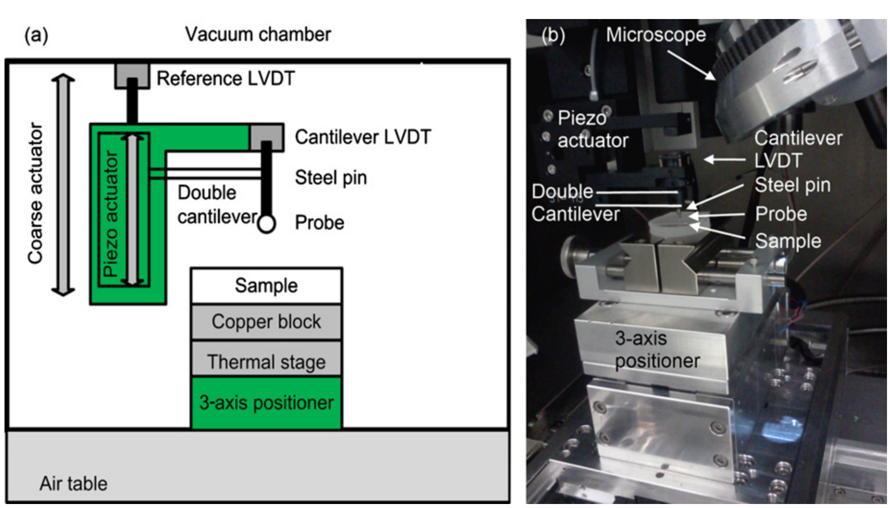

Fig. 2. Schematic (a) and photo (b) highlighting many parts of the NST. Not all parts appear in both images. Colour figure available online.