

Adhesion in a Vacuum Environment and its Implications for Dust Mitigation Techniques on Airless Bodies

*Stephen Berkebile and James R. Gaier
Glenn Research Center, Cleveland, Ohio*

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National Aeronautics and
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Glenn Research Center
Cleveland, Ohio 44135

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Stephen Berkebile¹ and James R. Gaier
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

During the Apollo missions, the adhesion of dust to critical spacecraft systems was a greater problem than anticipated and resulted in functional degradation of thermal control surfaces, spacesuit seals, and other spacecraft components. Notably, Earth-based simulation efforts did not predict the magnitude and effects of dust adhesion in the lunar environment. Forty years later, we understand that the ultrahigh vacuum (UHV) environment, coupled with micrometeorite impacts and constant ion and photon bombardment from the sun result in atomically clean and high surface energy dust particles and spacecraft surfaces. However, both the dominant mechanism of adhesion in airless environments and the conditions for high fidelity simulation tests have still to be determined. The experiments presented in here aim to aid in the development of dust mitigation techniques for airless bodies (e.g., lunar surface, asteroids, moons of outer planets). The approach taken consists of (a) quantifying the adhesion between common polymer and metallic spacecraft materials and a synthetic noritic volcanic glass, as a function of surface cleanliness and of triboelectric charge transfer in a UHV environment, and (b) determining parameters for high fidelity tests through investigation of adhesion dependence on vacuum environment and sample treatment. Adhesion force has been measured between pins of spacecraft materials and a plate of synthetic volcanic glass by determining the pull-off force with a torsion balance. Although no significant adhesion is generally observed directly as a result of high surface energies, the adhesion due to induced electrostatic charge is observed to increase with spacecraft material cleanliness, in some cases by over a factor of 10. Furthermore, electrostatically-induced adhesion is found to decrease rapidly above pressures of 10^{-6} torr. It is concluded that high-fidelity tests should be conducted in high to ultrahigh vacuum and include an ionized surface cleaning process.

Nomenclature

AZ-93	inorganic white thermal control paint
b_1, b_0	fitting parameters
F_{adh}	force of adhesion
FEP	fluorinated ethylene propylene
PC	polycarbonate
PTFE	polytetrafluoroethylene
RMS	root mean square
U_{strike}	energy of strike
UHV	ultrahigh vacuum

¹ NASA Glenn Research Center, NASA Postdoctoral Fellow, Oak Ridge Associated Universities.

Introduction

In the Review of United States Human Space Flight Plans Committee report of 2009, two of three paths considered to the final goal of Mars include travel first to the Moon or to “near-Earth objects ... and the scientifically interesting moons of Mars,” (Ref. 1). All of these bodies are airless bodies, with a vacuum environment exceeding that attainable in chambers on Earth, and are under constant bombardment by space plasmas, high energy particles, high energy electromagnetic radiation, and micrometeorites (Refs. 2 to 4). Additionally, the Moon, the moons of Mars and many asteroids are covered by a layer of regolith which contains a significant amount of fine to ultrafine particulate matter. Our experience with the Apollo missions showed that when exposed to dust in vacuum, the performance of thermal control surfaces is seriously degraded (Ref. 5), photovoltaic efficiency is decreased (Refs. 6 and 7), mechanical systems are compromised through abrasion (Ref. 5) and optical elements of cameras and telescopes are scratched or occluded (Ref. 8). As a result, these and other systems may fail when operating in a dusty vacuum environment if effective mitigation strategies are not developed and implemented.

Under the conditions of ultrahigh vacuum (UHV, $<10^{-9}$ torr) found at the surfaces of airless bodies, dust behaves very differently than in our atmosphere (Refs. 2 and 5). Dust adhesion properties are thought to be enhanced by two classes of mechanisms, increased surface energy and electrostatic attraction. Firstly, particles of dust are made more reactive through “space weathering” processes of ion bombardment and micrometeorite impacts which create smaller dust particles and freshly fractured surfaces. In UHV environments, the atomic cleanliness of freshly fractured surfaces is maintained and the population of chemically reactive surface species remains significant due to the scarcity of molecules in the gas phase colliding with the surface of the dust. The particle bombardment of the dust (and, with exposure time, the spacecraft materials) in the UHV environment results in the absence of a thin film of hydrocarbons and water that exists on surfaces in our atmosphere. As a result, the adhesion of dust is enhanced up to two orders of magnitude, primarily due to Van der Waals interactions (Ref. 9). The second mechanism which can enhance dust adhesion arises from electrostatic forces. For example, most lunar particles are composed of nonconductive minerals and glasses and will build up a equilibrium static charge under constant ion and photon bombardment (Refs. 10 and 11). Such effects lead to positive charge on the surface of the moon facing the Sun (photoelectric effect) and negative charge on the dark side (electrons from the solar wind) (Ref. 10).

As a result of space weathering under UHV conditions and the mechanisms listed above which lead to an increased adhesion, dust mitigation strategies which work under atmospheric conditions cannot be assumed to work on the surfaces of airless bodies. As the Apollo missions have shown, even tests in low to high vacuum environments can lead to misleading results which do not accurately simulate the lunar environment (Ref. 2).

In this study we address the issues of adhesion on airless bodies by using well-defined conditions which attempt to simulate a lunar environment combined with simple model systems of lunar and spacecraft materials to determine which mechanism, electrostatic or high surface energies, causes the greatest adhesion. To this end, the adhesion between pins of spacecraft materials and a plate of lunar simulant glassy material has been investigated in a UHV environment. The materials can be tested with control of their surface atomic cleanliness, as well as their electrostatic charge. This study includes measurements of adhesion due to both Van der Waals forces and electrostatic charging induced by triboelectric charging.

Until recently, it was unclear whether surface energy or electrostatic forces dominate for different particle sizes and for different types of dust. This investigation demonstrates that the electrostatic charge is the dominant mechanism of adhesion that can be expected in an airless body environment, and that particular attention must be given to issues of triboelectric charging. The triboelectric charge transfer is found to be sensitive to surface atomic cleanliness of the samples, and electrostatically induced adhesion is affected by background pressures exceeding 10^{-6} torr. Therefore, mitigation techniques should be tailored to deal with electrostatic forces. Furthermore, high fidelity tests and validation of dust mitigation techniques should include a step to remove surface contamination and be conducted in high to ultrahigh vacuum.

Experimental

This work aims to understand the adhesion forces between lunar dust and thermal control surfaces in the lunar environment, but the actual experiment necessarily makes several compromises. A torsion balance was used to measure the pull-off force (Ref. 12), so only macroscopic samples could be used. A plate of synthetic noritic volcanic glass with a lunar-like composition (Zybek Advanced Products, Boulder, CO) was used in place of the lunar dust. As determined by Auger electron spectroscopy, the chemical composition of the synthetic noritic glass surface is approximately 48 percent O, 18 percent Si, 16 percent Ca, 12 percent Al, and 6 percent Mg. The synthetic glass was produced by melting noritic materials from the Stillwater mine and quench cooling them. This material is also used as a source for the glass content in NU-LHT lunar regolith simulant. Lunar vacuum was simulated in an ultrahigh vacuum (UHV) chamber which was pumped to a vacuum of 10^{-10} torr or better, but still two orders of magnitude higher than lunar vacuum. Ion bombardment by the solar wind was simulated by sputtering the surfaces with Ar^+ ions.

The spacecraft materials were in the form of polished 3.2 mm diameter pins with hemispherical ends (radius = 1.6 mm). Most pins were polished mechanically with diamond paper down to 0.1 μm . Polycarbonate (PC) was polished with AlO_x paper and then chemically polished with a methylene chloride vapor. Mylar and Tedlar were used in the form of sheets spanned over an aluminum pin of the above curvature with no further treatment. Soda-lime glass was melted to the desired curvature. Silicone rubber S0383-70 (Parker Hannifin) was obtained in the form of an o-ring seal with tube radius of 1.3 mm and ring diameter 9 mm. AZ-93 paint (zinc orthotitanate in a potassium silicate binder) was applied to an aluminum pin (AZ Technologies, Huntsville, AL) and used as-received. All samples were rinsed in pure ethanol prior to placement in the UHV chamber. A list of the materials used can be found in Table 1 next to the root-mean-square surface roughness as measured by a Veeco/Wyko NT 1000 optical profilometer and the Young's moduli of the materials.

The experimental details have been described fully previously (Ref. 13), but the concept is straightforward. The hemispherical end of the pin being measured is driven towards the glass plate with a speed of 9.3 $\mu\text{m/s}$. It continues to be driven until the plate is pushed back which twists the torsion wire. After being displaced to a load of 0.1 to 0.5 mN, as measured by a differential variable reluctance transducer (DVRT) which measures the position of a balance arm on the opposite side of the plate, the drive motor is halted, and the pin and plate remain in contact for a specified, but variable, period of time, usually 15 to 30 sec. Then the pin is withdrawn from the plate at the same speed. After passing the torsion balance equilibrium point, the wire tends to pull the plate and pin apart. Separation occurs when the spring force equals the adhesion force. Examples of the raw data can be found in Reference 13.

TABLE 1.—APPROXIMATE RMS ROUGHNESSES OF PLATE AND PIN SURFACES BEFORE ADHESION MEASUREMENTS IN THE UHV CHAMBER AND YOUNG'S MODULUS OF MATERIALS (FROM ENGINEERINGTOOLBOX.COM)

Material	RMS roughness, nm	Young's Modulus, GPa
Noritic glass plate	<30	50 to 90
PC	90	2.6
PTFE	130	0.5
FEP	250	0.5
Ti-6-4	300	114
Al-6061	170	69
Soda-lime glass	-----	50 to 90
Mylar (boPET)	110	2 to 2.7
Tedlar (PVF)	150	-----
Silicone rubber S0383-70	620	0.001 to 0.005
AZ-93	-----	-----

A variation on the procedure was used to apply an electrostatic charge. The pin was placed 50 μm from the plate. It was then quickly brought into contact with the plate in a striking motion and retracted. Under many conditions this resulted in the deposition of charge on the pin, the plate, or both. This motion resulted in one large and several smaller bounces between the pin and plate. The strength of the strike was registered by the greatest displacement of the balance due to the strike. This displacement was then converted into potential energy from which the kinetic energy of the strike was assumed. The magnitude of charge deposition was inferred from the measured electrostatic adhesion force. The adhesion force was measured three to ten times after a strike at the strike position and was generally found to have little variation for any particular strike. The standard deviation of the adhesion measurements for a single strike is given as error bars in the figures.

Two types of adhesion forces could be observed, electrostatic and non-electrostatic (Van der Waals, chemical), which were distinguished by their functional dependence on separation and therefore their range. Measurements of the adhesion force were made under different loads, typically in the range of 0.1 to 0.5 mN. The duration of the loads was 30 sec for the measurements of non-electrostatic adhesion whereas the loads were typically maintained 15 sec for cases of electrostatic adhesion. No dependence on the load duration or magnitude was seen for electrostatic adhesion. The adhesion force values given throughout this report are generally the average of three or more contacts with the standard deviation shown as error bars.

The surfaces of the materials were cleaned by bombardment with 8.5 $\mu\text{A}/\text{cm}^2$ beam of Ar^+ ions accelerated to 2 keV from an ion gun (sputter cleaning). This process removed atmospheric contamination due to water and organic compounds from mineral surfaces and created a number of broken bonds, both of which leave the surface in a state similar to that which dust particles have in an airless body environment. Metals were sputtered until no improvement in the C and O surface contamination could be discerned using an Auger electron spectrometer before each measurement. Plastic materials were sputtered for 30 sec to 5 min each day before measurements. No dependence on sputter duration was seen after the initial sputter cycle. The synthetic volcanic glass was cleaned through ion bombardment prior to all measurements, unless explicitly stated.

Adhesion in UHV Environment

Non-Electrostatic Adhesion

The adhesion force due to Van der Waals and other short range interactions, such as chemical bonding, was below the apparatus detection limits ($-5 \mu\text{N}$) for most of the glass and pin sample pairs. (Since adhesion is an attractive force it is given a negative sign. Applied loads are positive in sign.) Forces as high as 10 mN were applied to press the pin and plate together, and were held as long as 10 min. The results were the same whether the volcanic glass was tested “dirty” or had been sputter cleaned, and whether the pin was dirty or cleaned.

There were three exceptions which displayed some form of non-electrostatic adhesion: the PTFE and 6061 aluminum pins and the S0383-70 o-ring. Interestingly, these three materials are different in their chemical and material properties, as well as the typical applications for which they are utilized. PTFE is often used when a non-stick surface is desired, while the silicone rubber S0383-70 is a candidate material for docking seals, an application in which gas-impermeable contact is sought. Al-6061 is a structural material which is not generally considered for its adhesive properties (or lack thereof).

In the case of PTFE, the adhesion force ranged from -0.02 to -0.10 mN, and depended on the magnitude of the applied force in a roughly linear fashion for any particular contact position (Fig. 1). However, the adhesion varied widely between contact locations, even for similarly treated samples. Leaving the pin attached to the glass at a load of 1.9 mN for a period of 2 hr resulted in an increase in the adhesion force by a factor of 5 to 10 over 30-second-long loads. Sputter cleaning the glass increased the adhesion force by about a factor of 4. Cleaning both the glass and the PTFE pin increased the adhesion an additional factor of 2 for some positions.

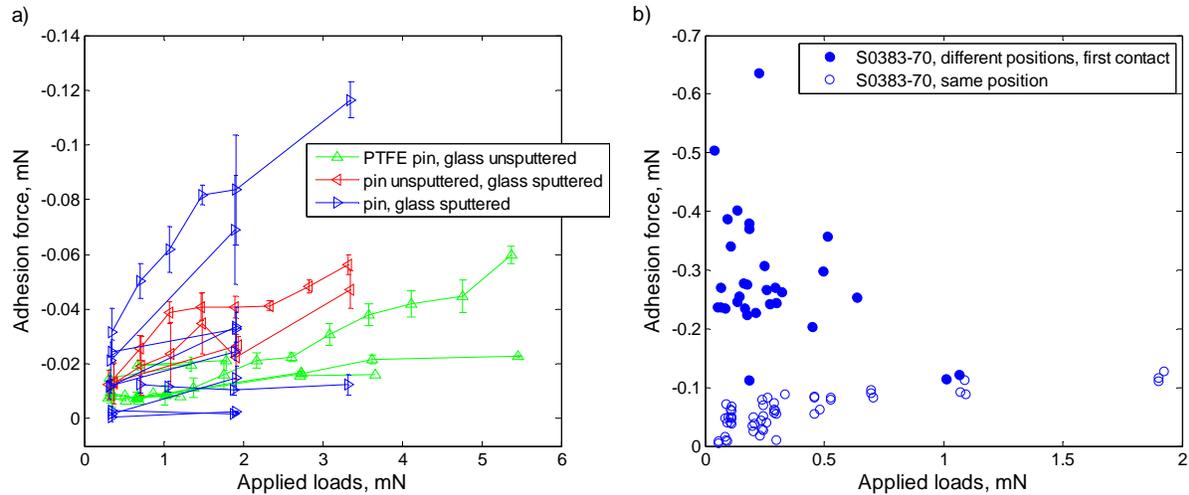


Figure 1.—Adhesion force due to Van der Waals and chemical interactions as a function of load for a) PTFE pin and b) S0383-70 silicone rubber o-ring on synthetic volcanic glass. Measurements of different loads at any particular contact position are connected by lines in a).

S0383-70 displayed non-electrostatic adhesion on sputter-cleaned glass when the o-ring was not treated after insertion in the vacuum system. The adhesion behavior was fairly erratic and varied greatly depending on the particular contact location selected, even though these locations were all of the same geometry. The adhesion for first contact at any particular location ranged from -0.1 to -0.65 mN, but was not dependent on the applied load, as can be seen in Figure 1. Further contacts at the same position always resulted in a greatly reduced adhesion force which would reduce within two to four contacts to a steady value between 20 percent of the original value to non-measurable. If adhesion was measurable for further contacts, these were found to be load-dependent, as shown for a particular location in Figure 1. When the o-ring was sputter cleaned, the non-electrostatic adhesion was no longer measurable, perhaps due to chemical modification of the surface through the breaking of bonds. Note that atomic oxygen treatment of such samples leads to a glassy surface which decreases total adhesion under large loads (Ref. 14).

The 6061 aluminum pins adhesion ranged from -0.01 to -0.08 mN and exhibited behavior that was difficult to interpret. Contrary to expectations, the adhesion force decreased at higher applied forces. Although there was a wide range of adhesion values, all values greater than -0.02 mN occurred when the applied load was less than 0.4 mN.

The mechanisms of non-electrostatic adhesion for these three samples can only be speculated on, but some evidence of the mechanisms is available from the conducted measurements. The S0383-70 displayed the largest adhesion, which then reduced with further contacts, suggesting that the position of contact was changing. Indeed, some evidence of material transfer was observed, in that the volcanic glass plate sometimes showed a tendency to charge during Auger electron spectroscopy measurements after numerous contacts were made. Although no significant amount of carbon was seen to transfer to the surface (and Si and O were already present in large amounts in the glass), a change in the secondary electron emission characteristics clearly occurred. It is possible that a chemical interaction is taking place at the silicone/silicate interface which is stronger than the cohesive force of the silicone rubber, with further Van der Waals forces present after chemical modification is complete. No transfer of Al or Mg was seen from the glass plate to the o-ring.

The smaller adhesion of the PTFE to the glass is unlikely to be chemical in nature, as PTFE is one of the most chemically inert substances known. PTFE is subject to creep of the polymer chains due to the lack of cross-linking. The load- and time-dependent adhesion values observed suggest that physical deformation of the PTFE tip is occurring. We propose that, even though PTFE is known to have low Van der Waals adhesion values, by conforming to the glass surface, the roughness of the PTFE is overcome and a large enough contact area is created for Van der Waals adhesion to become significant. Due to the smoothness of the glass, the mechanism of adhesion is not likely to be from mechanical interlocking.

Triboelectric Charging

Electrostatic adhesion was induced through triboelectric charge transfer between the spacecraft materials and the glass plate. Figure 2 shows the electrostatic adhesion force for individual strikes each with a particular strike energy, as calculated from the balance deflection due to the strike. As is shown in Figure 2, this triboelectric charge transfer increased with strike energy over the range of the strike kinetic energy, 1 to 15 μJ , which indicates that electrostatic adhesion forces increased with the amount of charge transferred upon striking the pin to the plate. Comparisons of adhesion data are more clearly illustrated in Table 2, which shows the average adhesion per unit strike energy. This value was determined by dividing the adhesion measured in a particular experiment by the kinetic strike energy applied. Thus, materials with higher values converted more of the kinetic energy into charge separation, which resulted in greater electrostatic adhesion.

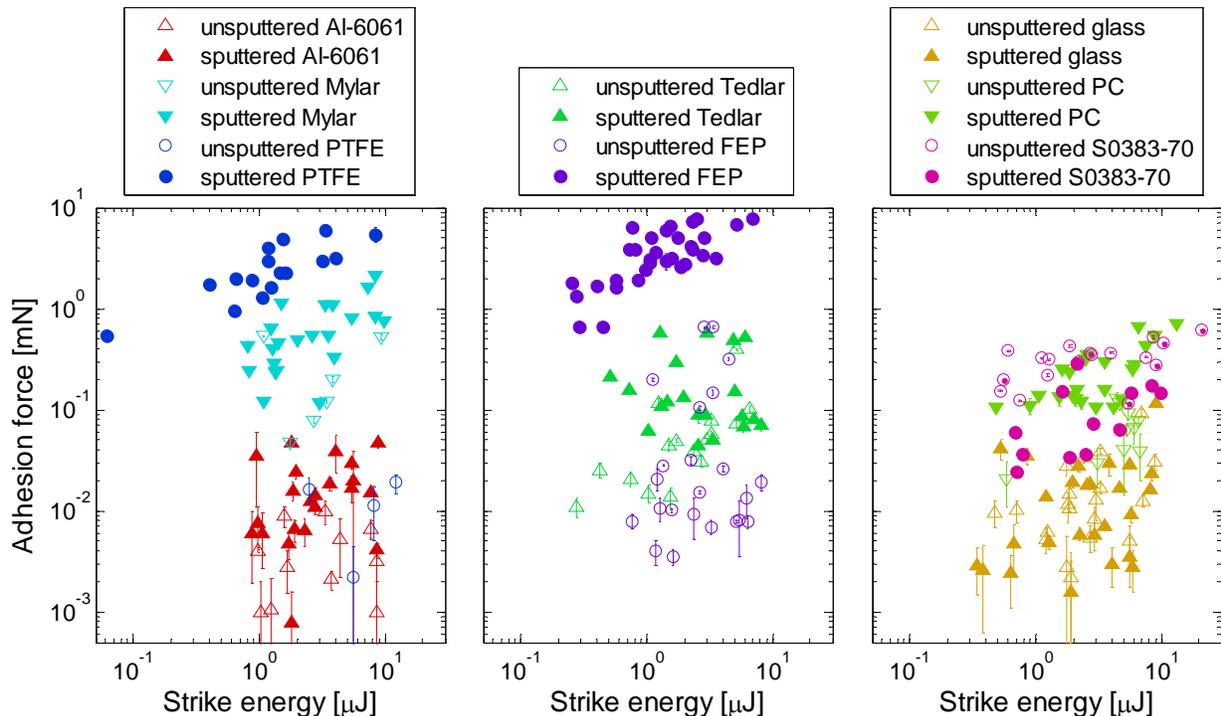


Figure 2.—Measured electrostatic adhesion force as a function of the kinetic energy of striking the pin against synthetic volcanic glass. Note that all logarithmic axes are equal for the three graphs.

TABLE 2.—MEASURED AVERAGE ELECTROSTATIC ADHESION FORCE PER KINETIC ENERGY OF THE STRIKING OF THE PIN AGAINST SYNTHETIC VOLCANIC GLASS

Material	Triboelectric affinity, nC/J*	Average adhesion force per strike energy, N/J	
		as is	sputter cleaned
Ti-6-4	---	‡	‡
Al 6061	---	-1.8	-7.4
Glass (soda lime)	+25	-7.2	-10.1
AZ-93	---	‡	‡
Polycarbonate	-5	-16.5	-84.4
Tedlar	---	-30.9	-105
Mylar	-40	-116	-240
Silicone rubber S0383-70	-72	-173	-43.9
PTFE	-190	-0.9	-2410
FEP	-190	-37.6	-3020

‡ Indicates non-detectable adhesion below -0.005 mN, i.e. about -0.3 N/J.

* from Triboelectric Table (Bill Lee, Alpha Lab Inc., 2009).

A clear difference is seen for most materials between the low to non-measurable charge transfer of the state “as inserted” into the UHV chamber and the high charge transfer of the “sputtered” samples. Sputter cleaning was conducted for 15 sec to 2 min for any particular polymer, and until a clean sample was obtained for the metals. As noted elsewhere (Ref. 15), such sputter treatment corresponds to an exposure of a few hours on the lunar surface. The exception to this rule was the S0383-70, which had the largest average charge transfer in the unsputtered state. Once sputtered, the triboelectrically-induced adhesion values were decreased, reminiscent of the decrease seen in the adhesion values after sputtering for non-electrostatic adhesion in the previous section.

Table 2 lists the materials in order of their triboelectric affinity. A positive value tends to give up electrons and become positively charged, and a negative value tends to gain electrons and take on a negative charge. The synthetic volcanic glass probably has a triboelectric affinity near that of soda lime glass. Electrons are so mobile in metals that they do not retain charge. Note that the adhesion forces, particularly for the cleaned materials, are well correlated to the triboelectric affinity.

The strike energy values of 1 to 15 μ J correspond roughly to the kinetic energy of spherical silica particles 0.4 to 1 mm in diameter when dropped onto a surface from the height of one meter in Earth’s gravity. If such a particle strikes PTFE or FEP, the electrostatic adhesion induced will be 1000 times the force of gravity acting on that particle (or 10 to 100 times the force of gravity when striking other polymer materials). The situation will be similar on the lunar surface, despite having only 1/6 of the Earth’s gravity. Since the potential energy of a particle depends linearly both on its height above a surface and on the gravitational force, the electrostatic adhesion after a fall of one meter on the Moon will be $1000/6 = 167$ times that on Earth (which is still 1000 times the force of gravity on the Moon). Particles lofted by human activity through a trajectory with horizontal motion will have additional translational energy.

In order to see how the induced electrostatic adhesion might scale to smaller values, both linear and exponential fits were attempted. The results were less than satisfactory. An exponential fit

$F_{adh} = b_0 U_{strike}^{b_1}$, with exponents b_1 less than zero, seemed to fit best for the largest values of adhesion with sputtered FEP and PTFE, but no fit could be found which provided confidence. While there is little variation in the adhesion measured as the result of any particular strike (several measurements after a strike result in the small standard deviation shown by the error bars), there is a large scatter between values measured as the result of different strikes. The large scatter in the data likely arises from the method of striking, which, while providing an exact maximum strike energy, includes several smaller contacts for each data point shown. To resolve the question of scaling to smaller particle sizes, further measurements will need to be conducted.

Effect of Vacuum on Charged Adhesion

Surface cleanliness has been shown to be an important factor for the triboelectric charge transfer. After the initial Ar^+ ion sputter cleaning of the surfaces used in this study, the cleanliness will depend on the quality of the vacuum environment. Likewise, once the charge transfer has taken place, the persistence of the charge on the surface and, hence, the electrostatic adhesion depends on the quality of the vacuum environment. Mechanisms of discharging an electrically charged surface are numerous and include collisions with gas, conduction, electron/ion bombardment (directly through charge neutralization or indirectly through secondary emission), and photoelectric emission. Conduction can be aided by a layer of water on the surface in a humid environment or by the inner photoelectric effect creating free charge carriers in an otherwise largely insulating material. On an airless body, the methods of discharge will be limited to solar wind plasma currents, photoelectric emission, and conduction, the latter of which is negligible for the polymers considered here and largely irrelevant for the lunar regolith. In fact, Farrell et al. (Ref. 16) worry about the lack of the former two mechanisms for discharge of triboelectrically-induced charge in the craters of the lunar polar regions.

In the absence of background gases and electron or ion currents, strong electrostatic adhesion was observed here to persist for a period of at least several days with no significant degradation in a vacuum of 10^{-10} torr. For more details, see Reference 13 where only a small drop in the strength of the electrostatic adhesion is seen over several hours. To test the robustness of the electrostatic adhesion with variation of background pressure, Argon gas and air were leaked into the UHV chamber while measuring the adhesion force of an FEP pin to the glass after striking. Once the charged pin has been exposed to Argon or air at pressures around 10^{-6} torr, a drastic drop in the adhesion force occurs (Fig. 3(a) and (b), respectively).

The charge on the pin and on the glass plate could be observed by scanning electron microscopy as a large distortion in the image. It was observed that full discharge of triboelectrically induced charge areas could be achieved with 100s of $\mu\text{A}/\text{cm}^2$ in 1 to 2 sec.

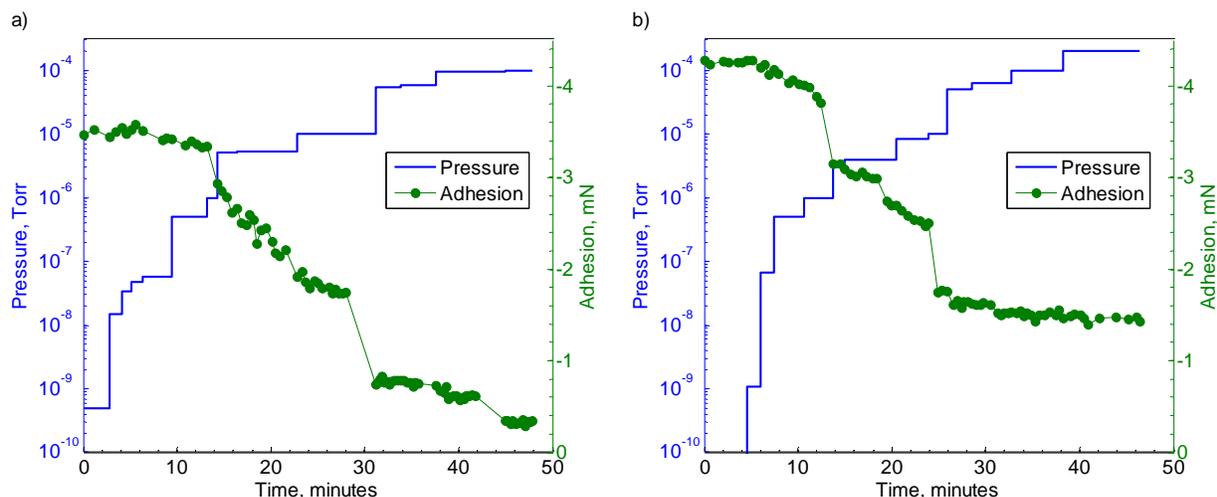


Figure 3.—FEP adhesion as a function of time during an increase of a) Argon pressure and b) air pressure.

Conclusion

In a UHV environment, triboelectric charging has been seen in this study to be the single greatest contributor to adhesion, particularly for atomically clean materials with large triboelectric affinities. The electrostatic adhesion was often orders of magnitude greater than Van der Waals forces or adhesion through chemical bonding, except in the case of silicone rubber. In the absence of plasma currents, such as in shadowed craters and sheltered areas of spacecraft triboelectric charging will dominate dust adhesion. In areas exposed to plasma currents or UV photons, triboelectric charging may be compensated (Ref. 16), but surface charge will still remain due to those same currents and photoelectric emission. As we have seen, charge can remain a significant source of adhesion over time scales ranging in hours and days in the absence of the atmospheric discharge effects of gas collisions and absorbed water.

Thus dust mitigation techniques which concentrate on reducing the effects of electrostatic forces will be much more successful over strategies which work to reduce Van der Waals adhesion. Through the use of coatings with a work function matching that of regolith minerals and glasses, or by choosing materials whose triboelectric affinity is similar to that of the dust, triboelectric charging can be limited passively. For example, the implications of triboelectric charging clearly favor the silicate-based paint AZ-93 over uncoated silver-FEP as the choice of thermal control surfaces where dust impingement is expected. In fact, a recent study has shown that work function matching coatings decrease dust adhesion to FEP surfaces in high fidelity tests with lunar simulant particles (Ref. 17). Such areas of heavy dust impingement are likely those where mechanical activities will occur, as a study by Katzan about the sources of lofted dust on the lunar surface revealed (Ref. 11). It should be noted that the dust environment around asteroids is far less known than on the lunar surface. The reduction of triboelectric charging should certainly determine the choices of materials used where intense contact with regolith will occur, such as in mining operations, under any conditions. Active manipulation of the dust and spacecraft surface charge electrostatically, as well as other electrostatic or electrodynamic mitigation techniques (see Ref. 18 for an example) will likely also prove most effective at mitigating dust adhesion.

When testing any mitigation strategies, the vacuum conditions within the test chamber and the monolayer surface contamination of regolith simulant and spacecraft materials are critical and will determine the applicability of any such test to a true airless body environment. Micrometeor impacts and the solar wind will ensure that the dust on the surface of any airless body will be atomically clean, while spacecraft materials will be cleaned by the solar wind within minutes to hours (Ref. 15). Contamination from water and hydrocarbons present on any surface which has been exposed to a terrestrial atmosphere greatly lowers the triboelectric charge transfer, and hence the adhesion. Removal of this contamination layer through a sputtering process or by plasma treatment will be an important step of any high fidelity test. Maintenance of a high to ultrahigh vacuum to prevent later accumulation of surface contaminants will be equally important. Maintenance of a vacuum below 10^{-6} torr will also be critical to avoiding discharge of any charged surfaces through collision with background gases. Although no significant drop in the adhesion was observed at 10^{-7} torr and below, we recommend that long term (hours) adhesion tests are performed and compared to adhesion loss rates in Reference 13 in order to qualify vacuum chambers for further tests. Ultimately, high fidelity tests and validation of dust adhesion mitigation technology must be made in high or ultrahigh vacuum and include a cleaning step of the regolith simulant and any exposed spacecraft material surfaces.

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14. ABSTRACT During the Apollo missions, the adhesion of dust to critical spacecraft systems was a greater problem than anticipated and resulted in functional degradation of thermal control surfaces, spacesuit seals, and other spacecraft components. Notably, Earth-based simulation efforts did not predict the magnitude and effects of dust adhesion in the lunar environment. Forty years later, we understand that the ultrahigh vacuum (UHV) environment, coupled with micrometeorite impacts and constant ion and photon bombardment from the sun result in atomically clean and high surface energy dust particles and spacecraft surfaces. However, both the dominant mechanism of adhesion in airless environments and the conditions for high fidelity simulation tests have still to be determined. The experiments presented in here aim to aid in the development of dust mitigation techniques for airless bodies (e.g., lunar surface, asteroids, moons of outer planets). The approach taken consists of (a) quantifying the adhesion between common polymer and metallic spacecraft materials and a synthetic noritic volcanic glass, as a function of surface cleanliness and of triboelectric charge transfer in a UHV environment, and (b) determining parameters for high fidelity tests through investigation of adhesion dependence on vacuum environment and sample treatment. Adhesion force has been measured between pins of spacecraft materials and a plate of synthetic volcanic glass by determining the pull-off force with a torsion balance. Although no significant adhesion is generally observed directly as a result of high surface energies, the adhesion due to induced electrostatic charge is observed to increase with spacecraft material cleanliness, in some cases by over a factor of 10. Furthermore, electrostatically-induced adhesion is found to decrease rapidly above pressures of 10 ⁻⁶ torr. It is concluded that high-fidelity tests should be conducted in high to ultrahigh vacuum and include an ionized surface cleaning process.					
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