Improving controllable adhesion on both rough and smooth surfaces with a hybrid electrostatic/gecko-like adhesive

Donald Ruffatto III1, Aaron Parness2 and Matthew Spenko1

1 Department of Mechanical, Materials, and Aerospace Engineering, Illinois Institute of Technology, Chicago, IL 60616, USA
2 NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

This paper describes a novel, controllable adhesive that combines the benefits of electrostatic adhesives with gecko-like directional dry adhesives. When working in combination, the two technologies create a positive feedback cycle whose adhesion, depending on the surface type, is often greater than the sum of its parts. The directional dry adhesive brings the electrostatic adhesive closer to the surface, increasing its effect. Similarly, the electrostatic adhesion helps engage more of the directional dry adhesive fibrillar structures, particularly on rough surfaces. This paper presents the new hybrid adhesive’s manufacturing process and compares its performance to three other adhesive technologies manufactured using a similar process: reinforced PDMS, electrostatic and directional dry adhesion. Tests were performed on a set of ceramic tiles with varying roughness to quantify its effect on shear adhesive force. The relative effectiveness of the hybrid adhesive increases as the surface roughness is increased. Experimental data are also presented for different substrate materials to demonstrate the enhanced performance achieved with the hybrid adhesive. Results show that the hybrid adhesive provides up to 5.1 times greater adhesion than the electrostatic adhesive or directional dry adhesive technologies alone.

1. Introduction

Controllable (i.e. on–off) attachment mechanisms, such as suction, electromagnets, microspines, fibrillar (gecko-like) and electrostatic adhesives, are used in a wide variety of applications and each tend to perform well on a specific surface type. For example, suction and fibrillar adhesives work well on smooth surfaces, microspines work well on rough surfaces and magnets work well on ferromagnetic surfaces. However, these adhesives generally fail when applied to a different surface type. For instance, suction fails on porous or rough surfaces and microspines cannot adhere to smooth surfaces. By contrast, this paper presents a novel adhesive that combines the properties of electrostatic and gecko-like dry adhesives to create an adhesive that can operate on smooth, micro-rough, curved, flat, conductive and non-conductive surfaces alike (see figure 1). In fact, on rough surfaces, the adhesive often outperforms the sum of its individual parts. The hybrid electrostatic/dry adhesive (EDA) could offer many benefits in a wide variety of applications that range from manufacturing to mobile robots that climb vertical and inverted surfaces to satellite grappling in space.

Manufacturing lines commonly use suction-based systems to perform pick and place operations for manipulation, assembly and palletization. While widely used, these systems have several drawbacks including the need for support equipment such as compressors and tubing, on/off lag time on the order of several seconds, and limited ability to grip porous or rough surfaces. By contrast, EDAs require little to no additional support equipment, have a low lag time and can adhere to both porous and rough surfaces.

In an effort to get mobile robots to climb vertical surfaces, researchers have employed almost every type of controllable adhesive, including magnets [1],
suction [2], microspines [3,4], gecko-like fibrillar dry adhesives [5–7] and electroadhesives [8]. Similar work has been undertaken in the area of perching micro air vehicles on walls and ceilings [9]. However, these types of robots are not widely deployed in the field owing to the simple fact that in most situations, an operator does not have prior knowledge of the surface with which the robot will interact. With an EDA, a robot can reliably adhere to a wider range of surfaces, thus reducing the need for a priori identification.

Many space applications require the ability to grapple objects [10,11]. Prior demonstrations of in-space grappeling have all relied on cooperative targets with a pre-determined grapple point. However, many objects do not have predefined grapple points, such as orbital debris and satellites in need of refurbishment. To attach to these objects, several potential controllable adhesive technologies have been developed, but each has limitations in space. Suction-based grippers are obviously ineffective in vacuum environments, and magnetic grippers will only be suitable for a small number of potential targets. Microspines could be useful for grappling natural surfaces like asteroids and comets [12], but they will not be effective on smooth, man-made surfaces. Again, EDAs could solve many of these potential problems owing to their ability to adhere to both smooth and rough surfaces of different materials.

EDAs work well on such a variety of surfaces because the two technologies, electrostatic adhesion and gecko-like dry adhesion, complement each other. Electrostatic adhesion uses a set of conductive electrodes deposited inside a dielectric. Applying a high voltage potential across the electrodes generates an electric field, which creates an adhesive force on both conductive and non-conductive substrates [13]. Dry adhesives, which are modelled on gecko feet, rely on intermolecular van der Waals forces and require a large number of very small fibrillar structures to make contact with the surface. This creates a microstructure that is resistant to crack propagation and whose normal adhesion levels can be controlled by applying an appropriate amount of shear force. The combination of the two technologies creates a positive feedback cycle whose whole is often greater than the sum of its parts. The directional dry adhesive can physically bring the electrostatic adhesive closer to the surface, which helps the electrostatic adhesive generate more adhesion. Consequently, the electrostatic adhesion helps engage more of the directional dry adhesive stalks, especially on rough surfaces.

Figure 1. The EDA comprises a silicone microstructure with an embedded electrode pattern. The microstructure (b) provides gecko-like dry adhesion, while the electrode pattern (a) generates electrostatic adhesion, demonstrating improved performance over either technology alone, especially on rough surfaces. (Online version in colour.)

The following sections provide background on electrostatic and gecko-like dry adhesives, describe the fabrication and testing process, and analyse and discuss test results.

Figure 2. Cross section of a simple electrostatic adhesive. (Online version in colour.)

2. Background

This work builds upon two different adhesive technologies: electrostatic adhesion and gecko-like directional dry adhesion. As such, this section describes previous work done in these two areas and previous researchers’ attempts to combine the technologies.

2.1. Electrostatic adhesives

Electrostatic adhesion works by applying a voltage potential across an array of conductive electrodes embedded in a dielectric (see figure 2). The resulting electric field generates an adhesive force on both conductive and non-conductive substrates. For conductive surfaces, electrons are free to migrate toward the positive electrodes and form electron holes under the negative electrodes. This essentially creates a set of capacitors in which the ‘plates’ are the electrodes and substrate. On non-conductive surfaces, the electric field polarizes the substrate’s molecules, which creates an attractive force [14].

For most materials, the polarization of the molecules, \( P \), is proportional to the strength of the applied electric field

\[
P = (\varepsilon_r - 1)E,
\]

(2.1)

where \( E \) is the electric field strength and \( \varepsilon_r \) is the dielectric constant of the material. The electrostatic adhesion force is then given by [14]

\[
F = PE.
\]

(2.2)

Therefore, the adhesion force is proportional to the square of the electric field strength, which is in turn dependent on a number of factors including the dielectric constant, dielectric thickness, voltage potential and electrode geometry. Previous research has shown that increasing the dielectric constant, decreasing the dielectric thickness or increasing the applied voltage potential all serve to increase the electric field strength [14].

Researchers have also attempted to evaluate the effect of electrode geometry on the electric field strength. This includes experimental studies [15,16] and the development of mathematical models of the electrostatic force [17–19]. The authors’ previous work [20] examined a wider design space using a finite-element analysis optimization tool in order to determine the optimal electrode geometry (see figures 2 and 3). The
authors found that a concentric circle pattern generated the highest electric field strength. Furthermore, they experimentally demonstrated that optimal electrode widths exist and range from 1 to 7 mm depending on a particular electrode’s location with respect to the other electrodes.

Previous researchers have also used a variety of techniques to fabricate electrostatic adhesives. One approach was to create the electrode pattern and then spray coat it with a thin layer of photo-resist resin as an insulator [15]. This works well on smooth surfaces because the photo-resist resin layer is extremely thin, thus increasing the electric field strength. However, with this technique, the electrostatic adhesive is unable to conform to surface irregularities, thus limiting it to smooth surfaces. Another method uses metal or carbon traces sandwiched between flexible Mylar sheeting [8]. This design affords some conformity to surface curvature but still does not address surface roughness. A different manufacturing technique was developed by Ruffatto et al. [20] that involves embedding a copper and nickel-coated conductive mesh inside a soft silicone dielectric. The conductive mesh is chemically etched with a ferric chloride solution to create an electrode pattern. Using a multi-step process, the mesh is embedded inside a soft, Shore 30A–40A, silicone rubber. This process yields a highly compliant electrostatic adhesive pad with high surface friction properties and an overall thickness of approximately 450 μm. This allows the pad to conform to micro-rough surfaces and create a large real area of contact. We use this same process, with only a slight modification, to create the EDAs described in this paper.

Figure 3. Different possible electrode geometries for an electrostatic adhesive. (Online version in colour.)

Figure 3. Different possible electrode geometries for an electrostatic adhesive. (Online version in colour.)

2.2. Directional dry adhesives

How geckos adhere to walls was a subject of scientific dispute for many years; however, in the early 2000s, researchers discovered that van der Waals forces are the primary contributor [21]. This discovery, coupled with improved microscopic imaging and microscale fabrication capabilities, kicked off a still-growing field of the design and manufacture of synthetic directional dry adhesives. Like the features on the toes of gecko lizards, directional dry adhesives use asymmetric microstructured hairs that create a high real area of contact when loaded in a preferred direction [22,23]. When the load is reversed, the adhesives release from the surface with near zero force. This property allows geckos to quickly attach and detach their feet when climbing walls [24].

Synthetic directional dry adhesives have yet to match the performance of live geckos, but significant progress has been made since the initial microstructures were fabricated more than a decade ago [25]. Summaries of these developments can be found in [26,27]. In general, synthetic gecko-like adhesives can be categorized into three types: submicrometre structures, isotropic microstructures and anisotropic microstructures.

Fibrillar submicrometre structures, like those presented by previous researchers [28,29], can show high levels of adhesion, but since the fibres lack a directional preference, they are generally sticky in all directions and cannot be detached from surfaces easily or efficiently. Owing to the relationship between fibre size and real area of contact [30], these submicrometre fibres can often be made of much stiffer materials, for example carbon nanotubes. Isotropic microstructures often use unique geometries at the tips of the fibres to increase the adhesion, for example mushroom-shaped caps [31–33]. The performance of various tip shapes was characterized in previous work [34], showing that the mushroom shape enhances adhesion by several fold over a flat tip shape. Finally, anisotropic microstructures use the directional preference of the adhesive’s shape, similar to the structures on a gecko toe, to turn adhesion on and off easily [35–37].

This paper builds off of previous work [38], which developed an anisotropic microstructure made of silicone rubber through a moulding process. These adhesives showed reusability out to 30 000 trials, which matches favourably with the performance of geckos [39], demonstrated a strong directional preference and were successfully deployed on a climbing robot [40].

2.3. Combination of electrostatic and directional dry adhesives

As previously discussed, electrostatic and directional dry adhesives each have advantages. Synthetic directional dry adhesives are capable of providing very high adhesion forces but are currently limited to smooth surfaces. Electrostatic adhesives, on the other hand, can function on a wide range of materials and surface roughness, but provide comparatively low adhesion forces. By combining these two technologies, it is possible to take advantage of their strengths and allow for operation on a wide variety of surfaces in terms of both material and roughness.

Previous attempts have been made to combine electrostatics with dry adhesives by only a few research groups. One group placed electrodes inside the dry adhesive microstructures [41]. Previous research by the authors showed that this is not optimal because the electric field is not able to disperse in the substrate [20]. Another approach was to fabricate a non-directional fibrillar adhesive using a conductive silicone [42]. Two separate pads are placed on a non-conductive substrate, one is grounded while a high voltage potential (2–4 kV) is applied to the other. The electrostatic adhesive in this arrangement provided a normal preload force for the non-directional dry adhesive, allowing it to make proper surface contact. The ability to self-preload yielded large improvements in shear and normal adhesive forces, though in practical application this configuration has limited versatility. As the conductive electrodes are completely exposed, its operation is restricted to controlled laboratory environments and non-conductive substrates.

This paper presents a hybrid adhesive which incorporates both electrostatic and directional dry adhesives. Using the previously described technologies, a microstructured dry adhesive element is moulded directly into the contact surface of a silicone electrostatic adhesive (see figure 4). The
electrostatic adhesive is able to provide a normal adhesion force to preload the dry adhesive element and pull the EDA into the substrate for excellent surface conformation. The directional dry adhesive provides conformation to micro scale features, easy release properties and a high real area of contact. Owing to this, the hybrid adhesive demonstrates enhanced performance over a wide range of substrate materials and roughness. This greatly extends the adhesive’s operating envelope in comparison to other technologies.

3. Fabrication

We developed a fabrication process for EDAs that builds upon previous work dealing with electrostatic adhesives [20,43]. For the EDA, a gecko-like adhesive, termed microwedges, are moulded directly into the surface of the electrostatic adhesive. The fabrication processes are described in the following subsections.

3.1. Microwedges

Previous work describes the fabrication of arrays of anisotropic microstructures that have many gecko-like properties including directional adhesion (on–off behaviour) and high reusability [38]. The microstructure consists of angled fibres that are 20 μm at the base, 60–70 μm tall and 200 μm wide with a space of 20 μm between each fibre. When shear is applied in the preferential direction, these wedge-shaped fibres bend over, dramatically increasing the real area of contact and generating high levels of adhesion through van der Waals interactions. However, when this shear is released or not applied in the preferred direction, the fibres do not engage the surface and adhesion is negligible.

These fibres are fabricated in batches using a moulding process. Moulds are made from SU-8 using a two-step angled lithography procedure and silicone rubber is used as the casting material. The moulds are reusable, so after its initial fabrication many sheets of gecko-like adhesive can be cast with relative ease. Full details of the lithography recipe have been published in previous work [44].

3.2. Hybrid adhesive

The EDA is fabricated in the same manner as electrostatic adhesives developed in previous work [20] but with one major distinction: microwedges are directly moulded into the pad surface using a wax mould cast from an SU-8 master mould. A wax mould is used to reduce the demoulding force and thus the internal peeling forces included on the adhesive.

The EDA is manufactured by embedding a set of conductive electrodes inside of Shore 40A platinum cure silicone rubber, Plat-Sil 73-40, from Polytek Development Corp. The conductive mesh consists of a 51 threads cm$^{-1}$ polyester weave with a copper–nickel coating, which yields a resistivity of less than 0.015 Ω cm$^{-2}$. An electrode pattern is chemically etched into it by clamping the mesh in a mould and immersing it in a ferric chloride solution to remove the conductive coating from unwanted regions. After 4 min, the mesh is removed from the etching solution, thoroughly cleaned with acetone and wires are soldered on. In addition to providing the electrodes, the conductive mesh allows for distribution of shear loads across the pad and is a critical feature of the design.

The fabrication process for the EDA consists of a multiple step procedure. As shown in figure 5 step (a), a thin, approximately 150 μm, layer of silicone is spun onto a directional dry adhesive mould at 1200 r.p.m. The silicone is allowed to partially cure in an oven at 45°C for 15 min. Then a second layer is spin coated at the same speed (step b), and a conductive mesh containing the electrode pattern is embedded into the uncured silicone. It is again allowed to partially cure at the same temperature for 10 min. In step (c), a final layer of silicone is spin coated on top at the same speed to completely encapsulate the

![Figure 4](http://rsif.royalsocietypublishing.org/) Cross-sectional view of a EDA. Dry adhesive features (microwedges) are directly moulded into the contact surface behind which a set of electrostatic adhesive electrodes are embedded. (Online version in colour.)

![Figure 5](http://rsif.royalsocietypublishing.org/) Cross-sectional view of the manufacturing process for an EDA. (a) A thin layer of silicone is spin coated onto a 75 mm diameter wax mould of the dry adhesive. (b) A second layer is spin coated on top of the first one and the electrode pattern is gently embedded. (c) To encapsulate the electrodes, a third and final layer of silicone is spin coated on and allowed to cure. (d) The EDA is then removed from the wax mould. (Online version in colour.)
3.3. Controls
In addition to the EDA pads, we manufactured fibre-reinforced PDMS, electrostatic and directional dry adhesives with the same diameter, thickness and material to serve as controls in the experiments. The fibre-reinforced PDMS and electrostatic samples were fabricated using the same process as in previous work [20]. The dry adhesive control was evaluated by testing an EDA with the electrostatic element in its ‘off’ state. We chose these as controls for two reasons: (i) to isolate the effects of individual technologies and (ii) we were able to fabricate them with the same general manufacturing process. The latter allowed all the pads to possess the same mechanical properties such as stiffness and tear strength. Three samples were manufactured for each type of adhesive.

4. Experimental set-up and procedure
A range of experiments was performed to quantify the adhesion enhancements realizable through the use of the EDA. The tested substrate materials, experimental set-up and test procedure are described in the following subsections.

4.1. Experimental set-up
A test platform consisting of a 6-DOF force–torque sensor and a pneumatic air slide actuated through a variable pressure regulator evaluated the shear performance of the different adhesive technologies (see figure 6). The substrate is mounted directly to a force–torque sensor while the adhesive is mounted to an air slide oriented parallel to the substrate.

A simple test sequence detaches the adhesive from the substrate to generate shear force data as follows:

(1) the air slide is shifted forward and the adhesive is gently laid onto the substrate material (no preload is applied);

(2) if needed, a 5 kV DC/DC converter (EMCO Q Series) energizes the electrostatic adhesive and a 10 s delay is observed;

(3) the variable pressure regulator increases the force output of the air slide until the adhesive detaches from the substrate;

(4) force data are recorded from the 6-DOF force–torque sensor at 1 kHz using a National Instruments data acquisition board and LabVIEW;

(5) a third-order Butterworth filter with a cut-off frequency of 10 Hz is used to remove any unrepresentative load spikes caused by dynamic effects; and

(6) the peak shear force value is extracted and converted to a shear stress by dividing by the adhesive area, 18 cm².

It is important to note that while the filter in step 5 reduces the maximum recorded adhesion levels, we believe that it is necessary to filter out high-frequency vibrations that occur from the pneumatic slide and noise from the force–torque sensor. This conservative approach has been used before in similar experiments [38,45].

4.2. Substrate materials
Each adhesive was tested on a range of substrate materials to evaluate the adhesive’s performance with respect to surface material type. The materials ranged from common household materials such as painted drywall, finished wood, glass and steel to more exotic space-grade materials, such as carbon fibre sandwich panel, graphite M55J, thermal black paint on aluminium, copper-clad Rogers 4003, white beta cloth, reinforced Kapton and reinforced Kapton MLI film.

Additionally, each adhesive was tested on a set of ceramic tiles to evaluate the adhesive’s performance with respect to surface roughness. We used ceramic tiles because they possessed widely varying textures and roughness with the same underlying material. A total of 14 different tiles were selected and their surface roughness was measured using a profilometer (KLA-Tencor Alphastep 500). Measurements were taken along a 5 cm strip located at the centre of the tile from which the arithmetic, RMS and peak–peak roughness was calculated (see table 1). The tile samples exhibited a wide range of roughness values with RMS values ranging from 9 to 109 μm.

4.3. Test procedure
For each adhesive sample, a total of 10 trials were performed on each substrate material using the testing platform previously described. Before testing, each adhesive pad was thoroughly cleaned using masking tape to remove any dust or other contaminants. We found that any residue left by the masking tape did not artificially increase the adhesive levels as compared with when the pads were first tested immediately after fabrication. The remaining trials were then run consecutively. The resulting data were checked for consistency to ensure that there are no cycle life related effects. This allowed for the shear force and shear stress values to be directly averaged for further analysis.

5. Results and discussion
Tests were performed to observe two phenomena: the effect of surface roughness on adhesion and the performance of the EDA on a wide variety of materials. Each is described below.
Figure 7. Shear stress as a function of surface roughness for the four different adhesive technologies when tested on 14 different tile substrates. On the smooth tiles, all the adhesive technologies are very similar with the hybrid providing slightly improved performance. On surface roughness greater than 50 µm RMS, the hybrid EDA demonstrates the largest improvements in shear stress. (Online version in colour.)

Table 1. Surface roughness values of the tested tile substrates.

<table>
<thead>
<tr>
<th>tile</th>
<th>average $R_a$ (µm)</th>
<th>RMS $R_q$ (µm)</th>
<th>max profile $R_t$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.6</td>
<td>23.6</td>
<td>128</td>
</tr>
<tr>
<td>2</td>
<td>18.6</td>
<td>23.5</td>
<td>121</td>
</tr>
<tr>
<td>3</td>
<td>8.0</td>
<td>10.7</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>74.3</td>
<td>92.7</td>
<td>394</td>
</tr>
<tr>
<td>5</td>
<td>96.4</td>
<td>109.0</td>
<td>378</td>
</tr>
<tr>
<td>6</td>
<td>7.4</td>
<td>9.0</td>
<td>54</td>
</tr>
<tr>
<td>7</td>
<td>10.8</td>
<td>13.5</td>
<td>70</td>
</tr>
<tr>
<td>8</td>
<td>12.7</td>
<td>15.7</td>
<td>81</td>
</tr>
<tr>
<td>9</td>
<td>23.5</td>
<td>28.4</td>
<td>136</td>
</tr>
<tr>
<td>10</td>
<td>58.3</td>
<td>71.4</td>
<td>283</td>
</tr>
<tr>
<td>11</td>
<td>6.9</td>
<td>11.3</td>
<td>90</td>
</tr>
<tr>
<td>12</td>
<td>17.0</td>
<td>20.9</td>
<td>98</td>
</tr>
<tr>
<td>13</td>
<td>21.8</td>
<td>25.1</td>
<td>109</td>
</tr>
<tr>
<td>14</td>
<td>7.3</td>
<td>9.2</td>
<td>54</td>
</tr>
</tbody>
</table>

5.1. Surface roughness

Surface roughness has a direct effect on adhesive force. One of the primary advantages of the newly developed EDA is its ability to conform to surface irregularities and provide enhanced adhesion properties. To demonstrate this, tests were performed with all four adhesive technologies on 14 different ceramic tiles. For each adhesive, the peak shear stress with respect to the substrate RMS roughness is shown in figure 7.

As seen in figure 7, at relatively low levels of roughness (approx. less than 10 µm), all the adhesive technologies tend to show similar performance. For comparison, table 2 shows the performance of the EDA side by side with several results from literature where patch sizes of more than 1 cm² were tested. The vast majority of previous research has investigated smooth surfaces, but the focus of this research is predominately performance of these adhesives on rough surfaces. Tests presented by Jeong et al. [32] were also performed on semi-rough surfaces, for example the back of a silicon wafer (674 nm RMS), and on smooth surfaces with step sizes of up to 20 µm. The EDA has been tested on surfaces with a roughness more than an order of magnitude higher, up to 109 µm RMS. These surfaces also consist of roughness at many length scales, unlike the stepped surfaces. On what we consider to be smooth tiles, loosely categorized here as possessing an RMS roughness of less than 25 µm, the reinforced PDMS quickly demonstrates reduced performance in some instances. The hybrid EDA, microwedges and the electrostatic adhesive continue to perform approximately the same at these levels of roughness. Some of the tile samples have a low surface RMS value but larger macro surface features that are not accounted for in the roughness measurement. On these surfaces, the reinforced PDMS performs poorly because of its inability to conform to the macro scale surface features. By contrast, the electrostatic adhesive is able to generate a normal force and the micro wedge features on the dry adhesive provide natural compliance and pull the adhesive into the substrate as the stalks engage.

On rough surfaces, the EDA shows the greatest performance improvements (see figure 8). In these examples, the shear stress achievable using a hybrid EDA is greater than the sum of that achieved by the electrostatic and directional dry adhesives alone. Figure 8 shows that this is the case for the tiles with high surface roughness; greater than around 50 µm RMS. This is most likely due to the two technologies’ ability to directly complement each other. The electrostatic adhesive is capable of generating a normal force, which draws the pad into the substrate. This allows the dry adhesive microwedges to gain improved surface contact and engagement. As more of the microwedge features are loaded, they pull the pad closer to the substrate surface. When this occurs, the conductive electrostatic electrodes are also moved closer to the substrate, thus increasing their normal force. This creates a positive feedback loop that allows each technology to improve the other’s adhesion capability. Therefore, the hybrid EDA can maintain a high effectiveness even on rough surfaces, thus greatly expanding its operational envelope.

It is important to note the local maxima that can be seen in figures 7 and 8 at a roughness of 92.7 µm RMS. This seems to be counterintuitive, as it is expected that there would be correspondingly lower shear forces as the substrate RMS increases. Upon further inspection, this can be attributed to the difficulty in characterizing roughness as a single value. Figure 9 shows the raw profilometer data for tiles 4, 5 and 10. The first plot, tile 10, shows a very sharp jaggedness on the substrate surface; greater than around 25 µm RMS. This seems to be counterintuitive, as it is expected that there would be correspondingly lower shear forces as the substrate RMS increases. Upon further inspection, this can be attributed to the difficulty in characterizing roughness as a single value. Figure 9 shows the raw profilometer data for tiles 4, 5 and 10. The first plot, tile 10, shows a very sharp jaggedness in the measured data indicating that the substrate surface has a high-frequency roughness component. This can explain the poor performance achieved on this substrate with all of the adhesive technologies. The flexible nature and compliance of the EDA and controls appear to conform to low frequency roughness better than high frequency. This ultimately reduces the real contact area and thus shear stress. By contrast, tile 4 shows a relatively smooth and gradual surface profile. This leads to higher peak shear forces regardless of the higher RMS roughness measurement.
5.2. Material type

Tests were performed on a set of different substrate materials ranging from drywall and glass to composites and thermal blankets (see table 3). Performance on these substrates varied dramatically owing to differences in material properties and surface roughness. As seen with the tiles, the hybrid EDA demonstrates the greatest performance increase over the control adhesives on rough surfaces. The test data presented in table 3 are further broken down in figures 10–12 to demonstrate key points.

Figure 10 shows the test results for a group of substrates with an RMS roughness of less than 10 µm: glass, finished wood and steel. The results for all the adhesive technologies are fairly similar. The electrostatic and reinforced PDMS adhesives provide slightly higher shear stress, particularly in the case of the glass substrate. This can be explained by the plain silicone adhesive’s contact surface providing a higher real area of contact compared with microstructured dry adhesives if the substrate roughness is very low. Other research has shown microstructured adhesives to provide higher adhesion levels, but this has been with different test constraints such as rigidly mounted test samples and hemispherical substrate surfaces [5,48]. The flexible adhesives presented here can conform to surface irregularities at the macro level and thus, they provide high surface contact on substrates with minimal micro-roughness. Furthermore, the effectiveness of flexible fibre-reinforced PDMS at distributing shear loads across the entire pad [49] may also play a role in explaining why the PDMS outperforms the microwedges. Consequently, the electrostatic adhesive provides the peak shear performance because it is simply a reinforced PDMS with an added electrostatic force. Also note that the electrostatic element in both the electrostatic and EDA is able to increase the performance of the reinforced PDMS and dry adhesives in every test.

Figure 11 shows the test results for the textured graphite M55J, thermal black-painted aluminium and painted drywall. On these materials, the EDA generated the highest shear stress. As seen on the tile substrates, when the surface roughness is increased, the combined conformation ability of the electrostatic and dry adhesive allows the hybrid EDA to outperform the other technologies. On these substrates, the amplitude of the roughness was small enough so that the dry adhesive microwedges still performed well. They

<table>
<thead>
<tr>
<th>reference</th>
<th>adhesive area (cm²)</th>
<th>preload (kPa)</th>
<th>shear stress (kPa)</th>
<th>roughness − R² (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>live gecko [46]</td>
<td>2.27</td>
<td>small</td>
<td>90</td>
<td>n.a.</td>
</tr>
<tr>
<td>polycarbonate nanohairs [47]</td>
<td>1.0</td>
<td>10</td>
<td>47</td>
<td>n.a.</td>
</tr>
<tr>
<td>polyurethane slanted nanohairs with flat tip [32]</td>
<td>3.0</td>
<td>3</td>
<td>210</td>
<td>90 on 0.68 µm RMS</td>
</tr>
<tr>
<td>hierarchical slanted nanohairs with flat tip [32]</td>
<td>3.0</td>
<td>3</td>
<td>90</td>
<td>35 on 20 µm steps</td>
</tr>
<tr>
<td>interdigital Mylar electrostatic adhesive [8]</td>
<td>approximately 100</td>
<td>none</td>
<td>4</td>
<td>2 on drywall</td>
</tr>
<tr>
<td>EDA</td>
<td>18.0</td>
<td>none</td>
<td>49</td>
<td>33 on 21 µm RMS</td>
</tr>
</tbody>
</table>

Figure 8. Peak shear stress generated by the tested adhesives on the three roughest tile substrates from figure 7. (Online version in colour.)

Figure 9. Measured profilometer data for each of the high RMS roughness tiles which were shown in figure 8. (Online version in colour.)
Table 3. Adhesive performance on a range of different substrate materials.

<table>
<thead>
<tr>
<th>type</th>
<th>substrate</th>
<th>shear stress (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PDMS</td>
<td>electrostatic</td>
</tr>
<tr>
<td>interior</td>
<td>tile (1) rough</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>drywall painted</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>wood polyurethane coated</td>
<td>41.6</td>
</tr>
<tr>
<td>smooth</td>
<td>glass standard</td>
<td>60.4</td>
</tr>
<tr>
<td></td>
<td>1018 steel polished</td>
<td>34.8</td>
</tr>
<tr>
<td>paint</td>
<td>thermal black S13 on aluminium</td>
<td>0.1</td>
</tr>
<tr>
<td>composites</td>
<td>graphite M55J; textured</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>carbon fibre sandwich panel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>textured</td>
<td></td>
</tr>
<tr>
<td></td>
<td>reinforced Kapton KN-90W grid side</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>reinforced Kapton MLI film</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>white beta cloth 800-Dun-Met</td>
<td>0.1</td>
</tr>
<tr>
<td>miscellaneous</td>
<td>patch antenna copper-clad Rogers</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>4003 (copper side)</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 10.** Peak shear stress results on glass, finished wood and steel. The PDMS and electrostatic adhesives provide the greatest shear stress due to the high real area of contact they can generate on very smooth surface substrates. (Online version in colour.)

**Figure 11.** Peak shear stress results on textured graphite M55J, aluminium painted with thermal black (S13) and painted drywall. On these materials, the hybrid EDA provides the greatest shear stress improving on the performance of the dry adhesive. (Online version in colour.)

lagged just slightly behind the EDA. Of particular note is the dramatic decrease in performance of the reinforced PDMS adhesive. Without any type of structure to allow for small-scale surface conformity, the real area of contact is greatly reduced. When used with the electrostatic adhesive, the PDMS still provides good performance owing to the inherent normal force generation and hence surface conformation properties. It is at these surface roughness levels and greater that the EDA’s performance begins to distinguish itself from the other adhesives.

Finally, figure 12 shows test results for the substrate materials on which the EDA functioned particularly well. These included space-grade blanket materials and tile sample 1. For these cases, the hybrid EDA was able to outperform the shear stress generated by both the electrostatic and dry adhesive combined. These are direct cases where, as previously described, the hybrid’s performance can be greater than the sum of its parts. On the tile substrate, the combined electrostatic and dry adhesive element provides high surface conformation.

In the case of the blanket materials, the substrate is also flexible, which allowed greater conformation between the adhesive and substrate when subjected to direct normal force created by the electrostatic adhesive. The exception was the white beta cloth (800-Dun-Met) where the performance of the electrostatic adhesive was low even though the hybrid still performed well. This was due to the low polarizability of the material which greatly decreased the electrostatic force. In this instance, the electrostatic force was still enough to engage the dry adhesive element of the hybrid further demonstrating the advantages of the new adhesive material. Overall, the EDA demonstrates improved
performance over both electrostatic and dry adhesives on all substrate materials above a surface roughness of 10 µm RMS.

6. Conclusion

This paper presents a novel hybrid adhesive that combined fibrillar dry adhesive structures with an electrostatic adhesive. The resulting adhesive shear force was experimentally tested on a wide range of materials with varying surface roughness. The results indicate that the new technology greatly extends the range of substrate materials and roughness to which controllable adhesives can be applied. In some cases, especially on rougher surfaces, the resulting adhesion is greater than the sum of the parts (i.e. electrostatic and fibrillar adhesives). Future work involves creating a mechanism such that normal and shear loads can be applied to the adhesive and optimization of the fibrillar structures to take advantage of the electrostatic adhesive’s ability to preload the pad. Such a mechanism will have applications in manufacturing, mobile robots and grappling objects in a space environment.

Acknowledgements. Work carried out at the Jet Propulsion Laboratory, California Institute of Technology, is performed under a contract with the National Aeronautics and Space Administration. Government sponsorship acknowledged.

Funding statement. This work was supported by ONR grant no. N00014-10-1-0769 and a NASA Office of the Chief Technologist’s Space Technology Research Fellowship.

References


44. Parness A. 2010 Microstructured adhesives for climbing applications. PhD thesis, Stanford University, Stanford, CA, USA.


