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Symmetrical electroadhesives independent of different interfacial surface conditions

J. Guo, T. Hovell, T. Bamber, J. Petzing, and L. Justham
The Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom
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Current electroadhesive actuators cannot produce stable electroadhesive forces on the same substrate with different interfacial surface interactions. It is, therefore, desirable to develop electroadhesive actuators that can generate stable adhesive forces on different surface conditions. A symmetrical electroadhesive pad that is independent of different interfacial scratch directions is developed and presented. A relative difference of only 6.4% in the normal force direction was observed when the electroadhesive was facing an aluminium plate with surface scratch directions of 0°, 45°, 90°, and 135°. This step-change improvement may significantly promote the application of electroadhesion technology. In addition, this manifests that significant performance improvements could be achieved via further investigations into electroadhesive designs. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/), https://doi.org/10.1063/1.5000715

Controllable, inherently safe, robust, and reliable adhesion has always been an unmet technological demand in a range of real-life applications such as the pick-and-place of difficult-to-handle materials and robotic climbing. It is especially needed for applications where a sufficient range of surfaces (from smooth glass to rough concrete surfaces) and environmental conditions (from vacuum/space to humidity, warm, and even dusty environments) have to be encountered.

Electroadhesion is a promising and potentially revolutionary adhesion mechanism that can be employed to hold or grasp objects in domains such as space, high value manufacturing, robotics, and autonomous systems. Examples of where electroadhesion is in use include Electrostatic fixtures to hold work-pieces, an adhesive method for space missions such as material handling and controllable earth orbit grappling, electrostatic chucks for material handling and grasping in semiconductor industries, end effectors for gripping advanced composites and fibrous materials, an adhesion mechanism for climbing and flying robots, and material handling units for manufacturing automation and warehouse automation applications. This is due to certain advantages that electroadhesion has over other adhesion mechanisms such as pneumatic, magnetic, and bio-inspired methods. These advantages include enhanced adaptability, gentle/flexible handling, reduced complexity, and ultra-low energy consumption.

Electroadhesion, initiated by high-electric-field induced polarization or electrostatic induction, is a dynamic, electrically controllable, and interfacial electrostatic attraction between an electroadhesive actuator and a substrate.

There are 33 known variables influencing the interfacial adhesive force generated between the electroadhesive pad and the substrate, including voltage, electrode patterns, material properties, environmental conditions, and interfacial surface texture. Electrode pattern or electrode geometry is one of the main factors influencing the obtainable electroadhesive forces. Various electrode patterns have been designed and implemented for electroadhesive applications. These electrode geometries include one-electrode designs, double-electrode designs, comb shape designs, spiral shape designs, and concentric designs, among others. Understanding the effect of surface interactions between the interfacial surfaces is of great importance in understanding any interfacial phenomenon, such as the electroadhesion phenomenon. The interfacial surface interaction is another important but less comprehensively explored factor affecting the electroadhesive force obtainable. Previous results demonstrated that: (1) the rougher the substrate surface, the smaller the electroadhesive force would be, to some extent (this is because the increasing air inclusion and distance between the electroadhesive and the substrate cause a force reduction); (2) unstable adhesive forces would be obtained using both double-electrode and comb pad designs under different substrate surface conditions and the same substrate with differing surface scratch directions.

It is assumed that spiral and concentric electroadhesive pad designs can be independent of different interfacial surface interactions, thus producing stable adhesive forces on the same plate with different interfacial surface conditions. In order to verify this, a circular aluminium (Al) plate (thickness of 1 mm and diameter of 275 mm) was sanded by a 60 grit aluminium oxide sanding disc to produce a unidirectional surface scratch. One distinctive advantage of using a circular plate is that different surface scratch directions can be achieved by rotating the plate to a range of desired angles without sanding additional substrates. In this study, interactions between electroadhesive pads and surface scratch directions of 0°, 45°, 90°, and 135°, as shown in Fig. 1, were explored. Ten different areas from the plate, each 1.43 mm × 1.09 mm, were measured using an Alicona InfiniteFocus G4 (Alicona, Austria), with a ×10 objective. The standard

4Authors to whom correspondence should be addressed: guojianglong9085@sina.com and L.Justham@lboro.ac.uk
Gaussian filter and a cut-off length of 0.8 mm were used to characterize the measured data. End effects were managed using the Talymap software. Surface texture information of one measured area of the plate can be seen in Fig. 2. The root mean square height ($S_q$) value of the plate was $2.8 \pm 0.25 \mu m$.

Previous results presented that there was a relative difference of 127.1% in the normal electroadhesive force obtained for a polyester (PET) double-electrode electroadhesive pad when energized at 3.6 kV and exposed to the four surface scratch directions.\textsuperscript{19} In addition, there was a relative difference of 75.3% for a polyimide comb electroadhesive pad when energized at 4.4 kV and exposed to the four surface scratch directions.\textsuperscript{11} Note that the relative difference was defined here as: $(\text{maximum value} - \text{minimum value})/\text{minimum value} \times 100\%$. It is, therefore, desirable to develop electroadhesive pads that can produce stable adhesive forces at different surface conditions. In addition, the fundamental science causing the unstable adhesive forces obtained should be further investigated. The main objectives of this study were to (1) experimentally validate that spiral and concentric electroadhesive pads could bring slightly stable adhesive forces on the same substrate with different surface scratch directions, compared to other existing electroadhesive patterns and (2) experimentally evaluate a symmetrical electroadhesive pad that can produce significantly better/stable adhesive forces and propose potential explanations or assumptions to the rationale or reason behind the proposed design.

One concentric pad (inspired from the work published by Ruffatto et al.\textsuperscript{16}) and one spiral pad (inspired from the work published by Germann et al.\textsuperscript{20}) were developed using a cost-effective and customized electroadhesive actuator design and manufacture platform which was based on solid-ink printing, chemical etching, and conformal coating.\textsuperscript{17} The two pads were all made of a chemically etched thin copper laminate (a 20 $\mu$m/23 $\mu$m copper-PET bilayer, UK Insulations Ltd., UK) and a polyurethane (PUC, Electrolube, UK) coating. The electrode dimensions of the concentric and spiral pads were the same as the ones published previously.\textsuperscript{17} They were also tested using the electroadhesive “normal force” testing platform and procedure published previously.\textsuperscript{11,19}

In order to eliminate the effect of the dielectric thickness and surface texture on the adhesive force obtainable, during the tests, the PET side of the pads was used to face the Al substrate. Note that in order to show that the thickness and surface texture of the PET side of the copper laminate are relatively consistent, surface texture and thickness measurements of five completely etched and cleaned copper laminates were conducted. For the PET film surface texture measurement, five different areas of the PET side of each laminate were measured using a Zygo NewView 5000, with a Mirau $50\times$ objective. A stitch (4 columns x 5 rows) was applied. The standard Gaussian filter and a cut-off length of 0.25 mm were applied. End effects were also managed. The $S_q$ values of the five PET sheets were $0.062 \pm 0.013 \mu m$, $0.074 \pm 0.009 \mu m$, $0.058 \pm 0.011 \mu m$, $0.069 \pm 0.008 \mu m$, and $0.071 \pm 0.015 \mu m$. Surface texture information of one measured area of one PET surface can be seen in Fig. 3. For the PET film thickness measurement, five different places on each laminate were measured using a digital micrometer (Mitutoyo,
RS Components, UK). The thicknesses of the five PET sheets were 24 ± 2 μm, 23 ± 1 μm, 23 ± 1 μm, 24 ± 2 μm, and 23 ± 1 μm, manifesting that the thickness difference between the copper laminates was small. Whilst 2 μm is objectively small, in the context of electroadhesion, this could cause significant changes in the force level. In this instance, the variation in surface roughness outweighs the variation in the dielectric thickness, but it should be acknowledged that this value is only small in this instance.

The normal electroadhesive forces obtained from the concentric pad and spiral pad on the four surface scratch directions can be seen in Figs. 4 and 5, respectively. There were relative differences of 60.5% (see Fig. 4) and 49.2% (see Fig. 5) in the adhesive forces obtainable for the concentric pad and the spiral pad, respectively. Recently, Graule et al.8 published another concentric electroadhesive pad. Inspired by the design, a pad having the same geometry but different parameters was developed and tested using the same pad manufacture and testing platform aforementioned. The electrode width was 1.8 mm. The space between electrodes was 4 mm. The effective electrode radius was 86.6 mm. The normal electroadhesive forces obtained, when the PET side of the pad was facing the Al substrate with four surface scratch directions, can be seen in Fig. 6. There was a relative difference of 33.1% in the adhesive forces obtainable.

There is a slight improvement in the adhesive force stability using the Germann inspired spiral and Ruffatto concentric pads, compared to the comb and double-electrode pads presented before. This is maybe because for the double-electrode and comb designs, the interactions between the electric field distributions and the surface scratch directions are totally different, as shown in Fig. 7. The interactions between the electric field distributions and the surface scratch directions for the double-electrode and comb design, where the yellow arrow denotes the electric field direction.
field distributions and the surface scratch directions for symmetrical electroadhesive pads, such as the Graule inspired concentric design, are, however, slightly similar.

Then, do we have better and more robust electrode patterns that can produce more stable adhesive forces on different surfaces? Note that a “robust” electroadhesive electrode pattern, defined in this study, is that an electrode geometry that can help to produce stable electroadhesive forces on the same substrate with different surface textures. In order to have the same interaction between the electric field distribution and the four surface scratch directions, a symmetrical electroadhesive design, inspired by the design published by Graule et al., was developed. The pad manufacture procedure is demonstrated in Fig. 8 (which is the same as the one published previously).

The pad has the same electrode parameters as the Graule inspired pad. The normal electroadhesive forces obtained, when the PET side of the pad was facing the Al substrate with four surface scratch directions, can be seen in Fig. 9. There was a relative difference of only 6.4% in the adhesive forces obtainable. This was observed when the pad was facing the Al plate with the four surface scratch directions. This is because the interactions between the electric field distributions and the surface scratch directions are the same for the proposed electrode pattern. Note that all the four aforementioned pads were charged at 2.8 kV for 90 s (510 s’ charge dissipation time) and tested in the same experimental setup when the environment was controlled at a relative humidity of 55 ± 1%, a temperature of 22.5 ± 0.1 °C, and an ambient pressure of 1010 ± 1 hPa. The preload was 30 ± 1 N. All the electroadhesive pads were manufactured using the same manufacturing procedure as aforesaid. Five tests were conducted for each scratch direction. Averages of the five results for each scratch direction are presented with error bars standing for their standard deviations.

Understanding the interactions between electric field distributions and substrate surface scratch directions is important for designing optimized electroadhesives. Most current electroadhesive designs cannot bring stable adhesive forces at different substrate surface conditions due to inconsistent electroadhesive-surface interactions. In this study, it has been verified that symmetrical spiral and concentric designs can help to address this issue. A relative difference of only 6.4% in the normal electroadhesive force was observed when the pad was facing the Al plate with surface scratch directions of 0°, 45°, 90°, and 135°. Compared to the relative difference of 127.1% for the double-electrode design, 75.3% for the comb design, 49.2% for the spiral design, 60.5% for the Ruffatto concentric design, and 33.1% for the Graule concentric design, 6.4% for the proposed design is a significant (step-change) improvement in terms of adhesive force stability at different surface conditions.

FIG. 8. The electroadhesive pad manufacture procedure: (a) the proposed electroadhesive geometry was printed onto the copper side of an A4 sized copper-PET bilayer using a solid-ink (black wax) printer (Xerox UK Ltd., UK); (b) the wax printed copper laminate was then chemically etched to remove the unwanted copper area in a bubble etching tank (Mega Electronics Ltd., UK) filled with ferric chloride (RS Components, UK) etchant; (c) the etched laminate was then thoroughly cleaned using a label removal, iso-propyl alcohol, and acetone (Farnell element14, UK) successively; (d) the cleaned laminate was then spray-coated using the PUC and degassed and cured in a vacuum oven (Fistreem International Ltd., UK); (e) before testing, the pad was allowed to cool at room temperature for 24 h.

FIG. 9. Normal electroadhesive forces on the Al plate with different surface scratch directions using the symmetrical pad design.
may significantly promote the application of the electroadhesion technology. Collaborative efforts and continuous investigations are, however, still necessary to develop better electroadhesives to produce more stable adhesive forces. In addition, robust electroadhesives are always needed as there are various reasons that may cause the failure of electroadhesive pads, including (1) small gaps between electrodes that may induce dielectric breakdown, (2) sharp electrode corners and rough electrode edges that may increase chances of charge concentrations, (3) low quality dielectric material coatings that may introduce air bubbles or defects, and (4) material aging and degradation.

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1K. Rahbek, U.S. Patent US2025123A (1935).
2R. W. Warning, Phys. Forces Electrostatiques Appl. I, 17–27 (1960).
3G. P. Beasley and W. W. Hankins, in Weightlessness and Artificial Gravity Meeting, Williamsburg, Virginia, USA (1971).
4B. Leung, L. Miller, N. Goeser, and S. Gonzalez, in IEEE Aerospace Conference, Big Sky, Montana, USA, 2015.
5G. Shim and H. Sugai, Plasma Fusion Res. 3, 051 (2008).
6G. I. Monkman, Int. J. Rob. Res. 14, 144–151 (1995).
7R. Liu, R. Chen, H. Shen, and R. Zhang, Int. J. Adv. Rob. Syst. 10, 1–9 (2012).
8M. Graule, P. Chirarattananon, S. Fuller, N. Jafferis, K. Ma, M. Spenko, R. Kornbluh, and R. Wood, Science 352, 978–982 (2016).
9Grabit Inc., see http://grabitinc.com/ for the benefits of using electroadhesion from Grabit Inc. (last accessed July 2017).
10J. Guo, L. Justham, M. Jackson, and R. Parkin, Key Eng. Mater. 649, 22–29 (2015).
11J. Guo, M. Tailor, T. Bamber, M. Chamberlain, L. Justham, and M. Jackson, J. Phys. D Appl. Phys. 49, 35303 (2016).
12J. Guo, T. Bamber, M. Chamberlain, L. Justham, and M. Jackson, J. Phys. D Appl. Phys. 49, 415304 (2016).
13R. Chen, Y. Huang, and Q. Tang, J. Adhes. Sci. Technol. 31, 1229–1250 (2017).
14J. Guo, T. Bamber, M. Chamberlain, L. Justham, and M. Jackson, IEEE Rob. Auton. Lett. 2, 538–545 (2017).
15T. Bamber, J. Guo, J. Singh, M. Bigharaz, P. A. Bingham, L. Justham, J. Petzing, J. Penders, and M. Jackson, J. Phys. D Appl. Phys. 50, 205304 (2017).
16D. Ruffatto, J. Shah, and M. Spenko, J. Electrost. 72, 147–155 (2014).
17J. Guo, T. Bamber, T. Hovell, M. Chamberlain, L. Justham, and M. Jackson, IFAC-Pap. Online 49, 309–315 (2016).
18C. Cao, X. Sun, Y. Fang, Q. Qin, A. Yu, and X. Feng, Mater. Des. 89, 485–491 (2016).
19J. Guo, T. Bamber, J. Petzing, L. Justham, and M. Jackson, Appl. Phys. Lett. 110, 051602 (2017).
20J. Germann, M. Dommer, R. Pericet-Camara, and D. Floreano, Adv. Rob. 26, 785–798 (2012).