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Increasing adhesion via a new electrode design and improved manufacturing in electrostatic/microstructured adhesives

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ABSTRACT

This paper characterizes a new electrode design coupled with new fabrication methods to improve the performance of electrostatic/microstructured adhesives. The design is similar to a parallel plate capacitor in which one plate has “holes” or gaps. The gaps allow the electric field to “leak” through, which can, under certain circumstances, create a stronger electric field than a conventional design. The design was optimized using FEA, and experimental results show that combining the new design with an improved fabrication method that increases the flexibility of the adhesive results in a 6× increase in the shear stress to disengage the adhesive from the substrate.

1. Introduction

Controllable (i.e. on-off) adhesives, such as suction [1], electromagnets [2], microspines [3], and microstructured (i.e. fibrillar, gecko-like, dry) [4] tend to perform well on a specific surface type, but fail when applied to an alternate surface. For example, suction and microstructured adhesives work well on smooth surfaces, but fail on rough surfaces. In the case of microstructured adhesives, the surface roughness, which may be as slight as the texture left behind from a paint roller, can prevent the adhesive from engaging with the substrate.

In an effort to create an adhesive that is applicable to both smooth and rough surfaces, previous work has combined electrostatic adhesives and microstructured adhesives (see Fig. 1 [5]). By applying a voltage potential across an array of conductive electrodes embedded in a dielectric, an electrostatic field is generated, which results in an adhesive force on both conductive and non-conductive substrates. The combination of the two technologies creates a positive feedback loop. The electrostatic adhesive helps engage the fibrillar stalks which in turn bring the electrodes closer to the surface. As the electrodes move closer to the surface, the electrostatic adhesive force increases. The result is an adhesive that has been shown to outperform the sum of its individual parts on many surfaces [5]. The resulting adhesive has potential in a variety of applications that range from manufacturing [6], mobile robots that climb vertical and inverted surfaces [7–14], perching micro air vehicles [15–18] and satellite grappling in space [19].

This paper presents an electrode design for the electrostatic portion of the electrostatic/microstructured adhesive that theoretically increases the normal adhesion by up to 3.5×. The paper also introduces a new manufacturing process that improves the flexibility of the adhesive pad to further increase the adhesion pressure. Experimental results show a 6× increase in the shear stress needed to disengage the adhesive from a substrate compared to a traditional design. In contrast to other approaches, the design layers the electrodes on top of each other (see Fig. 2, left) instead of placing them in the same plane (see Fig. 1). The new design can be thought of as a parallel plate capacitor in which one of the plates has “holes” or gaps in it. The approach is counter-intuitive because the electric field is highest in the dielectric between the two electrodes, not on the substrate to which the adhesive is attaching. Thus, it is more reasonable to place the electrodes side-by-side. However, the spacing between electrodes in the traditional design is limited by the voltage breakdown strength of the dielectric used to encapsulate the electrodes. This is problematic as a smaller electrode gap results in a higher electric field strength and thus generally higher adhesion.

For the design introduced here, note the circled portion in the right image of Fig. 2 and how the gaps allow the electric field to essentially “leak” through to the substrate. Simulations demonstrate that this leakage can, under certain circumstances, generate a stronger electric field than the conventional in-plane design. This is due to the new design allowing the gap between positive and negative electrodes be significantly reduced, and gap size has a strong effect on adhesion pressure [20]. Smaller electrode gaps are possible because the new

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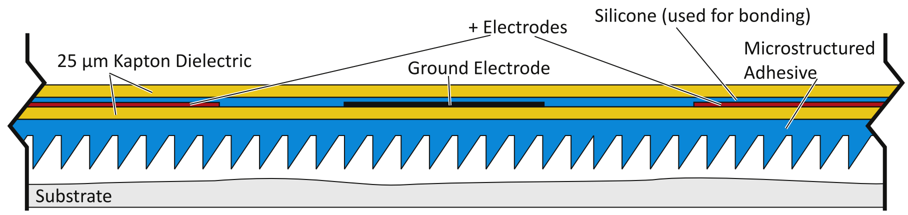

Fig. 1. Cross-sectional view of a traditional electrostatic/microstructured adhesive design in which the both positive and ground electrodes are placed on the same layer. Drawn to scale.

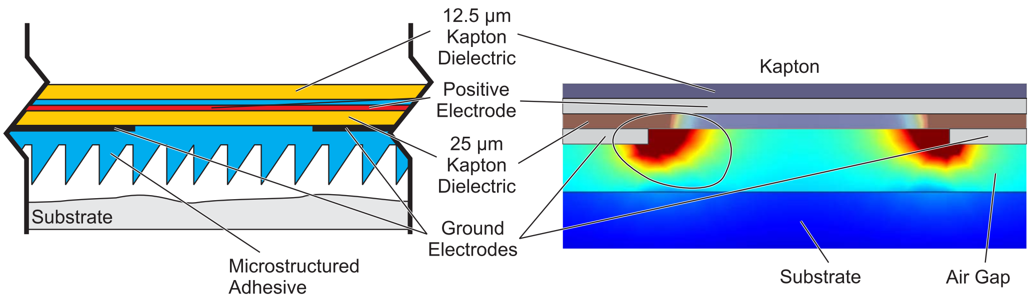

Fig. 2. The new layered design (cross-section, left) puts the positive and ground electrodes on separate planes in an effort to decrease the gap size and utilize a dielectric layer with a high dielectric voltage breakdown strength (e.g. Kapton). The right side shows a cross-section of the simulation results of the electric field strength using this design. Drawn to scale.

design employs an insulating dielectric with a relatively high voltage breakdown constant (e.g. Kapton). Thus, less distance is required between electrodes to prevent voltage breakdown. Note that in [21], due to their manufacturing process, a Mylar sheet is placed between layers of inter-digital electrodes to act as the dielectric. The effect is similar to the one presented here; however, this paper will demonstrate why that approach works and how a solid backing electrode results in the strongest electrostatic field.

This paper is organized as follows. First, Section 2 provides background information regarding electrostatic and microstructured adhesives. Section 3 then describes the simulation model used to optimize the overall geometry of the electrode pattern as well as the specific electrode widths and gap sizes. In Section 4, the fabrication procedure is introduced for both electrostatic adhesive designs. Section 5 then presents experimental test results to validate the simulation models. Finally, Section 6 summarizes the work.

2. Background

This work utilizes two different adhesive technologies: electrostatic adhesion and microstructured fibrillar adhesion. This section describes previous work done in both of these areas as well as work that has combined the two.

2.1. Electrostatic adhesives

In electrostatic adhesion, a high voltage potential (typically on the order of kV) across electrodes embedded in a dielectric creates an electrostatic field, which in turn creates an adhesive force [22]. The main advantage of electrostatic adhesion is that it can be applied to almost any substrate, both conducting and non-conducting. For conductive surfaces, electrons are free to migrate toward the positive electrodes and form electron holes under the negative electrodes. On non-conductive surfaces, the electric field polarizes the substrate's molecules, which creates an attractive force [20]. Due to its universality in terms of substrate composition, electrostatic adhesion has been used for grippers in the semi-conductor industry [23] and is especially applicable to space environments where ferromagnetic materials are rare, pressure sensitive adhesives out-gas, and suction does not work because of the lack of an atmosphere.

The magnitude of electrostatic adhesion force is related to a number of factors including the voltage potential, electrode geometry (e.g. width, gap spacing, pattern), insulator thickness, and substrate permittivity. Increasing the voltage potential or substrate permittivity improves adhesion force, as does decreasing the insulator thickness or gap size between electrodes [20].

Researchers have attempted to evaluate the effect of electrode geometry on the electric field strength. This includes small experimental studies [24] and the development of mathematical models of the electrostatic force [25,26]. Some of the most complete studies to date were [27] and [28], which both examined the entire design space using a Finite Element Analysis optimization tool in order to determine the optimal electrode geometry. Still other work evaluated adhesion with theoretical studies coupled with finite element simulations [29] and experimentally investigated adhesion as a function of substrate roughness [30].

Previous researchers have also used a variety of techniques to fabricate electrostatic adhesives. One approach created the electrode pattern using polyethylene terephthalate and then spray coated it with a thin layer of photo-resist resin as an insulator [31]. This works well on smooth surfaces because the photo-resist resin layer is very thin, thus increasing the electric field strength. However, with this technique the electroadhesive is unable to conform to surface irregularities, thus limiting it to smooth surfaces. A counter to that is the work done by [32], which examined the fabrication of stretchable electrodes.

Another method used metal or carbon traces sandwiched between flexible Mylar sheeting [14]. This design affords some conformity to surface curvature but still does not address surface roughness. A different manufacturing technique was developed by the authors [27] 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 multistep process the mesh is embedded inside of a soft, Shore 30A–40A, silicone polymer. This process yields a highly compliant electrostatic adhesive pad with high surface friction properties and an overall thickness of approximately 400 μm. This allows the pad to conform to micro-rough surfaces and create a large real-area of contact. We use a similar fabrication process in this paper, substituting copper-clad Kapton for the conductive mesh.

2.2. Microstructured adhesives

Since the early 2000's, numerous researchers have been developing manufacturing techniques to fabricate artificial microstructured adhesives [34–36]. Synthetic fibrillar adhesives use multiple structures to engage with a surface to help reduce crack propagation and improve conformity to surface undulations. Some utilize asymmetric, or directional, micro-structured hairs that create a high real area of contact