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# Increasing the adhesion force of electrostatic adhesives using optimized electrode geometry and a novel manufacturing process

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ABSTRACT

This paper presents a method to increase the adhesion level of electrostatic adhesives by optimizing the electrode geometry and using a novel manufacturing technique. Simulation software, Comsol Multiphysics, was used to find the average electric field strength generated by a specific electrode geometry. The geometry was then optimized based on a gradient descent algorithm that changed each individual electrode width. Four different electrode patterns were simulated: concentric circles, comb (inter-digital), square spiral, and Hilbert curve (a fractal space-filling geometry). Among these designs the concentric circle pattern was the most effective. The optimized concentric circle pattern had varying electrode widths and the smallest allowable gap between the electrodes. These results were experimentally validated on a variety of materials with varying roughness: drywall, wood, tile, glass and steel. Overall, the experimental data closely matched the simulation results. Utilization of a new fabrication process also allowed for a significant increase in shear adhesion capability. With the optimized electrode geometry and the new fabrication process, we are able to achieve between a 2.2 and 15× improvement in shear pressure compared to previously published values, depending on the substrate material.


## 1. Introduction and background

Electrostatic adhesion [1] is used in the semiconductor industry for wafer and flat panel display handling [2], in the printing industry for toner adhesion, in the food and painting industry for powder coating, and in the robotics industry as attachment mechanisms [3]. The advantage of electrostatic adhesion is that it generates adhesion on a variety of surfaces ranging from glass and steel to rougher surfaces such as wood and concrete. This is in contrast to other adhesion methods such as micro-spines [4,5], suction [6], electromagnetics, pressure sensitive adhesives [7] and dry adhesives [8–10] that can be very surface specific. The disadvantages of electrostatic adhesives are that the adhesion level is relatively weak and it does not function on some plastics. This paper improves the adhesion level of electrostatic adhesives by:

1. examining and optimizing the relationship between adhesion force and electrode geometry; and
2. utilizing a novel fabrication method.

When a voltage potential is applied across a set of conductive electrodes (see Fig. 1) an electric field is generated. If the electrodes are immersed in a dielectric and placed on a substrate, an adhesive force is generated. In a conductive substrate, electrons are free to move throughout the conductor allowing them to migrate under the positive electrodes and generate electron holes under the negative electrodes. This causes the system to act as a set of capacitors where the plates of the capacitor are attracted to each other.

In non-conductive substrates, adhesion force is produced by the polarization of the substrate [11]. Polarization for most materials is proportional to the applied electric field and is defined as:

$$P = (\varepsilon_r - 1)E \tag{1}$$

where $E$ is the electric field strength and $\varepsilon_r$ is the dielectric constant of the material. The electrostatic adhesion force is given by: [11]

$$F = PE \tag{2}$$

Hence, increasing the magnitude of the electric field will enhance adhesion.

A number of factors including dielectric constant, dielectric thickness, voltage potential, and the geometry of electrodes determine the strength of the generated electric field. Increasing the dielectric constant, decreasing the dielectric thickness, or

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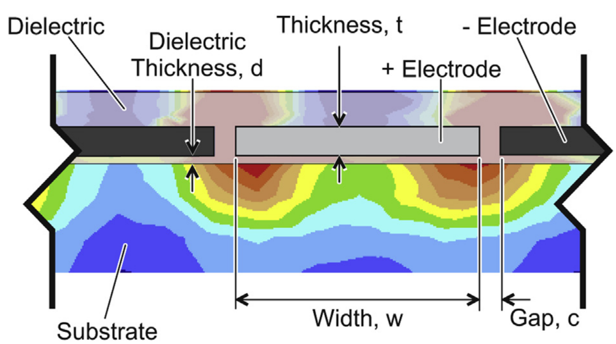


**Fig. 1.** Cross-section of an electrostatic adhesive pad.

increasing the applied voltage potential all serve to increase the electric field strength. These parameters are well understood, but the effect of the geometry of the electrodes is still unknown.

Previous researchers have experimentally compared a small handful of electrode geometries [12,13], and mathematical models of the electrostatic force have been developed [14,15]. In particular, researchers obtained 1.5 kPa of shear adhesion pressure on a polyethylene terephthalate sheet by keeping the gap between the electrodes at 1 mm and the width of the electrodes at 1 mm [12]. They tested three different electrode geometries: the comb pattern (sometimes referred to as inter-digital pattern), the square spiral pattern (see Fig. 2), and a simple two electrode model with an electrode gap spacing of 1 mm. From this they found that the comb pattern yielded the maximum adhesion force. However, the tests failed to consider a wider range of patterns or their entire design space, e.g. varying electrode width. Compared to this, our work examines the entire design space using Finite Element Analysis techniques to find the optimal electrode widths for a variety of electrode patterns (see Fig. 2).

Previous researchers have also used different techniques to fabricate electrostatic adhesives. One approach was to create an electrode pattern and then spray coat it with a thin layer of photoresist resin as an insulator [12]. The problem with this technique is that the electrostatic adhesive is not flexible or conformal to surface irregularities, thus limiting it to smooth surfaces. Another method was to use metal or carbon traces sandwiched between flexible mylar sheeting. This design affords some conformity to surface curvature but still does not address surface roughness [3]. In this paper, we develop a novel manufacturing technique 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 of a soft Shore 30A silicone polymer. This process yields a highly compliant electrostatic adhesive pad (see Fig. 3) 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.

This paper is based upon previous work by the authors [16] and provides an improved optimization algorithm, additional simulation results, and further experimental results. It is organized as follows. An overview of the simulation model, setup, and procedure is provided. Simulation results are shown and discussed. The electrostatic adhesion pad fabrication process, experimental test platform, and testing procedure are described. Experimental results on five different surfaces: glass, drywall, wood, tile, and steel are presented and compared with the simulation results. Finally, full shear/adhesive limit curves are demonstrated for the electrostatic adhesive with a hierarchical backing and concluding remarks are provided.

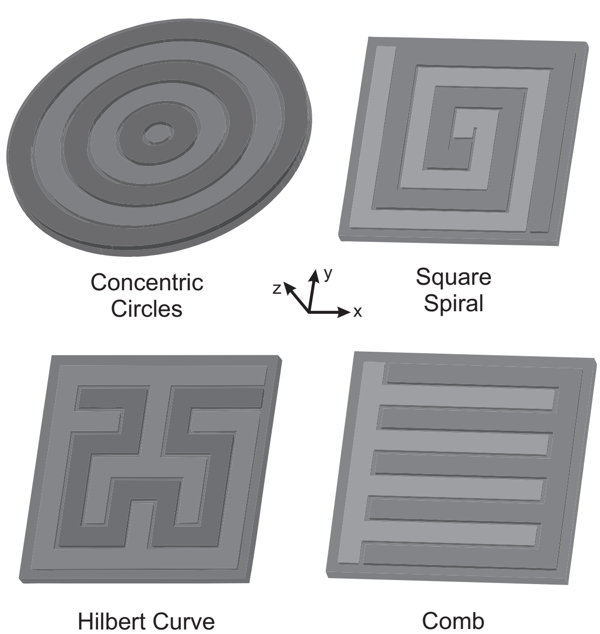


**Fig. 2.** Simulation models of different electrode patterns.

## 2. Simulation procedure

COMSOL Multiphysics was used in conjunction with Matlab to simulate and optimize the electrode pattern for the maximum electric field strength. This section describes the simulation model, setup, and procedure.

### 2.1. Model

COMSOL Multiphysics version 4.2, from COMSOL Incorporated, was used to simulate the different electrode geometries shown in Fig. 2. These patterns were chosen based on previous research and the authors' design concepts. The comb (inter-digital) pattern is the predominate configuration used by previous researchers and served as a control [3,14]. Additionally, the square spiral pattern has been previously investigated [12]. The Hilbert curve and concentric circles patterns were new concepts developed by the authors. The Hilbert curve represents a continuous space filling pattern while the concentric circles pattern minimizes corners. Additional patterns, such as a checker board configuration, were also initially investigated, but found to perform poorly.

A basic electrode model is shown in Fig. 1. The five parameters of the model that were investigated are the number of electrodes, the

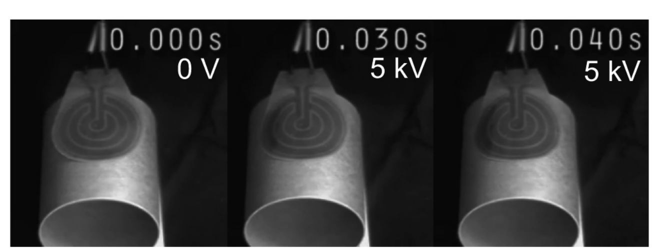


**Fig. 3.** High speed camera images of the conformal electrostatic adhesive adhering to a 65 mm diameter cardboard tube.