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Theoretical model and design of electroadhesive pad with interdigitated electrodes

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ABSTRACT

Electric fields alter adhesive forces between materials. Electroadhesive forces have been utilized in diverse applications ranging from climbing robots, electrostatic levitation to electro-sticky boards. However, the design of electroadhesive devices still largely relies on empirical or “trial-and-error” approaches. In this work, a theoretical model is presented to analyze the electrostatic field between the supporting wall and the electroadhesive device with periodic coplanar electrodes. The air-gap between the surface of electroadhesive device and the dielectric wall is explicitly taken into account in the model to consider its significant impact on electroadhesive forces. On the basis of this model, the electroadhesive force is calculated by using the Maxwell stress tensor. The effects of key design parameters and working environments on the electroadhesion behavior are further investigated. This study not only provides a tool to reveal the underlying mechanisms of electroadhesion but also suggests potential strategies to optimize novel electroadhesive devices for engineering applications.

1. Introduction

Electric fields can alter adhesive forces between materials, which allow surfaces to reversibly attach to each other without the use of mechanical grippers, suckors, fasteners, or chemical adhesives [1–6]. Electroadhesive devices have been developed by patterning electrodes in air or matrices of insulating dielectrics. Once an electric voltage is applied, the devices can invoke the adhesive forces to a wide variety of substrate materials (e.g., silicon, silicon dioxide, wood, drywall, glass, concrete, steel, and plastics) with various shapes, sizes, and roughness [2,5–7]. Compared to mechanical and chemical adhesions, the electroadhesion has distinct advantages, e.g., fast response (response time < 10 ms), quiet operation, low cost, easy control, low energy consumption, and dust tolerance [2]. Due to these many benefits, electroadhesive devices have been widely used in various applications. Examples include electrostatic levitation used in liquid-crystal-display manufacturing [4,8–12], electroadhesive grippers for handling microcomponents of semiconductors [13,14], and electroadhesive pads for wall climbing robots [2,5,6,15,16] and sticky boards [17].

An electroadhesive device uses the electrostatic force between the supporting material (e.g., wall surface) and the electroadhesive pad. For Coulomb-type electrostatic pads (ESP), the electrostatic force is generated by the dielectric polarization due to the electric potential difference. Based on the charge (or electrode) configuration, ESPs can be classified into two types: mono-polar (plate-plate-capacitors) and bipolar (interdigitated electrodes) [1]. Mono-polar type ESPs generate adhesive forces in accordance with the principle that the two plates in a parallel capacitor attract each other if there is a voltage difference between them. Therefore, the target structure (e.g., a concrete wall) is required to be conductive such that a capacitor is formed between the electrode and the supporting wall [18]. A bipolar type electroadhesive device is typically constituted by interlacing the fingers of two conducting combs, as shown in Fig. 1. The space between the electrode fingers is usually filled with an electrical insulator. The fingers and the filler are insulated from the substrate by a dielectric layer (i.e. the cover in Fig. 1). When alternating positive and negative charges are induced on the adjacent electrodes and the device is placed in contact with a wall, the electric fields set up opposite charges on the wall and thus cause electrostatic adhesion between the electrodes and the induced charges on the supporting wall. This force may be explained by two mechanisms, namely, the gradient force and the Johnsen–Rahbeck force [19].

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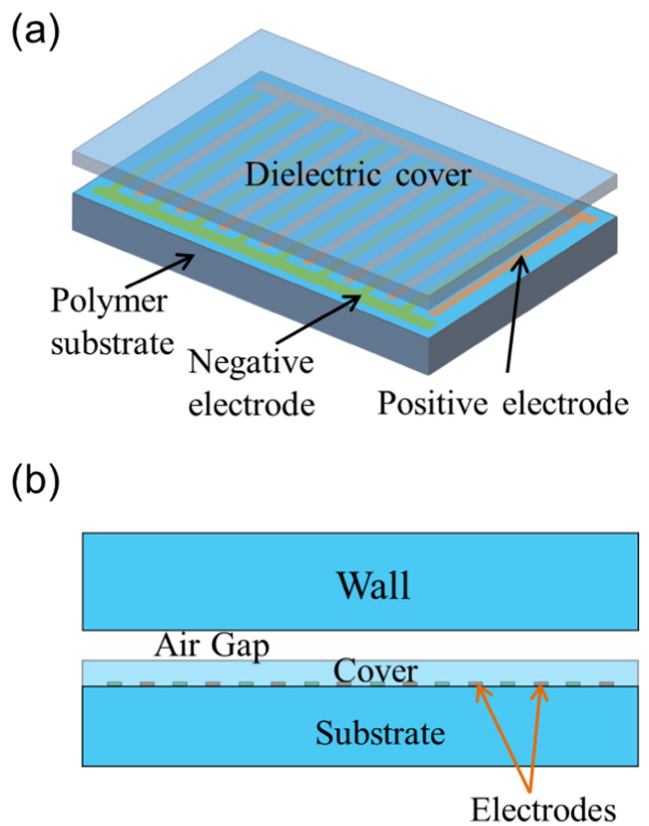

Fig. 1. Schematic of an electroadhesive pad with embedded interdigitated electrodes: (a) 3D view and (b) side view.

Despite these technologically important applications of electroadhesion, the design of electroadhesive devices has largely relied on trial-and-error approaches and the electroadhesive stresses and energy are usually estimated by empirical equations [2,7,10,13,15]. Prahlad and coworkers experimentally investigated the compliant electroadhesion technique and developed a variety of wall climbing robots such as tracked and legged robots [2]. They tested the attractive force of the robots climbing on distinct surfaces of materials and demonstrated the validity and superior performance of electroadhesion in climbing robots. Yamamoto et al. [15] designed a wall climbing robot with flexible electrodes that were fabricated by a plastic film and a conductive foil. They tested the attaching performance of the flexible electrode panel against both conductive and non-conductive walls, in which the adhesive forces is proportional to the square of voltage. Other innovative designs, e.g. gecko inspired electrostatic-chuck (ESC) [1], were also proposed to improve the poor performance of conventional ESCs on relatively rough surfaces. However, most of the studies were mainly experimental and there is still a lack of theoretical models to reveal the relationship between the adhesive force and the key design parameters. Optimal design principles are still unavailable for a majority of electroadhesive devices, in which the electrodes are actually embedded in insulating dielectrics. Only recently, Woo and Higuchi [9] developed a numerical model of electrostatic-levitation to calculate the forces generated by electrodes and discussed the optimization of the electric charging rate with respect to the geometrical parameters of electrodes.

In this paper, we attempt to theoretically address the basic design principles of electroadhesion. A semi-analytical method is presented to calculate the electric field in a four-layer or five-layer model. The Maxwell stress tensor is used to calculate the desired electroadhesive force. We demonstrate that various key factors, including the dielectric constants of constituent materials, the thicknesses of cover layer, the air-gap, and the supporting walls, as well as the applied voltage and the dielectric constant of walls, have significant effect on the performance of electroadhesive devices. This work not only helps in the comprehension of the adhesion mechanisms in electrostatic devices but also supplies guidance for their optimal design.

2. Model of electroadhesive forces

Consider an electroadhesive pad consisting of periodic coplanar electrodes sandwiched between a dielectric cover and a substrate, as shown in Fig. 1. Such electroadhesive pads can be made in a variety of methods. To enhance the compliance of the pad, the interdigitated electrodes can be deposited by flexible materials such as carbon mixed with a polymer binder [2] or crumpled metal film [20]. The cover and substrate can be made of elastomers, polymers or plastics with different dielectric constants while the supporting wall can be any common material, e.g. concrete cement or wood.

A four-layer model is here established, including the dielectric wall, the air gap, the cover, and the dielectric substrate. To investigate the electroadhesion, we first need to calculate the electric field distribution generated by the electrodes embedded in the electroadhesive device. It is well known that the electric field **E** in the solution space can be readily calculated from the electric potential ϕ by

$$\mathbf{E} = -\nabla\phi, \tag{1}$$

and that the potential in a dielectric medium satisfies the Laplace equation

$$\nabla^2\phi = 0. \tag{2}$$

When the solution domain of the problem is filled with a homogenous material, the electrostatic field can be analytically solved by the conformal mapping technique [21,22]. However, for a structure made of several different materials as shown in Fig. 2(a), the conformal mapping technique fails to solve the problem. Therefore, a point matching method is used here to calculate the electric fields [9,23]. In this method, the potential function in each layer is defined by a series expansion in terms of the solutions of the Laplace equation, which are periodic in the direction parallel to the electrodes. For different layers, the coefficients in the series are related to each other and to the electric potentials applied on the electrodes. The boundary conditions in the electrode plane are satisfied at N discrete points, with N being the number of terms in the series expansion [23]. The details of the calculation method are given in Supplemental information (SI) [24].

As shown in Fig. 2(a), the electroadhesive device consists of a coplanar array of electrodes whose uniform pitch and width are assumed to be $L = 2b$ and $2a$, respectively. The electrodes are assumed to have a negligible thickness and to be charged alternatingly by the electric potentials Φ and $-\Phi$. Due to the periodic feature of the electrodes, only one period of the structure is analyzed. More details of the model and the solution method are given in SI [24]. As shown in Fig. 2(b)–(d), using this four-layer model, we calculate the distributions of electric potential ϕ and electric field components E_x and E_y for one period of the structure with the assumed dielectric and geometric parameters $\varepsilon_w = 10\varepsilon_0$, $\varepsilon_c = 2\varepsilon_0$, $a/b = 0.5$, and $t/b = 0.02$, where ε_0 denotes the dielectric constant of air, $\varepsilon_w$is the dielectric constant of the wall (supporting substrate), $\varepsilon_c$the dielectric constant of the cover, and t is the air gap thickness between the electroadhesion pad and the wall. It can be seen that E_y is the dominating component and its intensity in the air gap is much larger than those in the dielectric wall and the cover, yielding a relative larger attractive force between the pad and the wall.

The electrostatic attractive force exerted on the dielectric plate arises from the interaction between the applied non-uniform electric field and