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Electrostatic Devices for Material Handling

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***Abstract*—This paper presents the investigation on electrostatic devices for material handling purpose. Few example of the device is tested for work piece attachment. It is shown that the adhesive force is at a useful level to hold a small work piece. The experiment also confirms the qualitative advantages of electrostatic adhesion, such as fast attachment, low power consumption, high force to mass ratio, and easy detachment. It also works on non-conductive work piece with fairly rough surface. Further actuating the electrostatic devices at higher voltage shows that only within a certain voltage level the *F* - *V* relation is quadratic as predicted by the parallel capacitor model. Beyond this range, saturation of output force is observed.**

***Keywords*—electrostatic devices, material handling**

I. Introduction

The development of applied electrostatic is well over a century with industrial application examples in electrostatic precipitation, painting and coating, and electrophotography. In material handling industry, the technique of applying electrostatic attachment force for grasp and release of parts is a viable replacement technology for conventional methods such as mechanical gripper, vacuum suction and magnetic adhesion. Various applications using electrostatic attachment include examples such as fabric handling [1-4], electrostatic chuck (ESC) for the pick and place of silicon wafer [5-8], and manipulation of objects [9-11] in general. In robotic applications, successful examples can be found in wall climbing robots [12-15]. These robots utilize the electrostatic force generated by the conveyor-like locomotive configuration for speedy climb movement on vertical surfaces.

The qualitative advantage of electrostatic adhesion is evident where it can be applied on a wide range of object material. Static force works well on both electrically conductive and insulating objects. Since principally an electrostatic device does not conduct electrical current ideally, the power consumption can be in the range of μW to mW. This opens the opportunity for emerging device applications which are ready to exploit the characteristics of electrostatic adhesion. However, the understanding of force generation is yet to be conclusive. Here we present a simple electrostatic gripper for holding a work piece, and also subsequent experiment to investigate force generation of such devices.

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II. Methodology

A. *Modelling of Electrostatic Device*

The parallel plane capacitor model constitutes the principal theory to derive the electrostatic force. When two conductors are connected to a voltage source *V*, one acquires a positive charge and the other acquires an equal magnitude of negative charge. The capacitance between the plates is given as C = $\varepsilon A/x$, where ε is the permittivity of the gap separating the plates, *A* is the area of the conductor, and *x* is the distance of separation for the two conductors. Energy stored as capacitance is given as $W=1/2CV^2$. By using work-energy method, differentiating the stored energy yields the electrostatic force:

$$F_e = \frac{dW}{dx} = \frac{V^2}{2}\frac{d}{dx}(C) \quad (1)$$

The theoretical electrostatic force model for an ESA actuator is given as [16]:

$$F_e = -\frac{\varepsilon_0 \varepsilon_r A V^2}{2d^2} \quad (2)$$

where ε_0 is the permittivity of free space (8.854 × 10^{-12} F.m^{-1}), ε_r is the relative permittivity of dielectric material, *A* is the contact area between electrode and object, *V* is the applied voltage, *d* is the thickness of the dielectric material, and the minus sign indicates that the force is attractive. It can be seen that the electrostatic (adhesion) force generated by the actuator is governed by material properties and geometrical properties of the dielectric and electrode, and acted upon by surface charge induced through applied high voltage. In order to obtain the F_e of several N, one can readily calculate that the *d* is in the range of 10^2 μm thickness and *V* is in the range of several kV. With this in mind, the design schematic of a simple electrostatic device may take the form of thin film, as shown in Fig. 1.

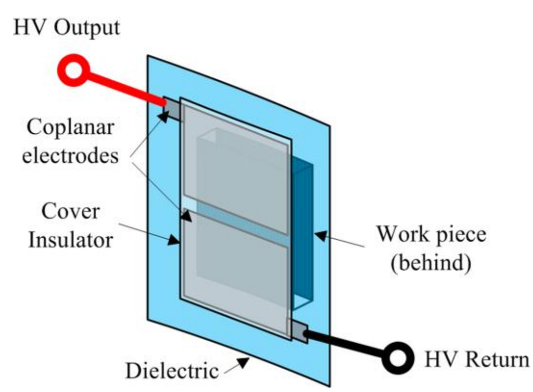

Fig. 1. Electrostatic device holding a work piece.

From (2) it is understood that the electrostatic device works best when the distance of separation is kept minimal between the electrode and work piece. Thus the thickness of the dielectric shall be kept low while not causing electrical breakdown. The dielectric strength of the dielectric determines the electric potential that it can withstand per thickness of material until electrical breakdown. This separation of distance can quickly become large when the electrostatic device is peeled away from the work piece. Thus peeling mechanism is not only a weakness of electrostatic device, but also a characteristic that can be exploited when quick detachment of work piece is desired.

Contact area is affected by the surface roughness of the work piece and the compliance of the dielectric on the work piece. The choice of material under various Shore A hardness readily determines the compliance level of the dielectric. That said, a highly compliance dielectric increases the effective contact area by minimizing the air gap that is trapped in between. Nevertheless, most high compliance material exhibits an elastomeric effect when contacts at most surfaces. The effect results in a “sticky” state or high coefficient of static friction between the material and surface.

Once an electrostatic device is designed with a defined material and geometrical parameters, the other controllable parameter is the applied voltage. From (2) one can assume that the force generated is quadratic-ally proportional to the voltage. However the subsequent experimental results presented shall reveal some other characteristics of this F-V relation. The distance between the co-planar electrodes and the dielectric thickness determine the maximum level of voltage that can be applied to the electrostatic device to prevent electrical breakdown. Spark, which is similar to lighting and also acoustic bang, which is similar to thunder can occur during breakdown of the dielectric. The dielectric material may be permanently damaged or self-recoverable during breakdown.

B. *Construction of Electrostatic Device*

3 types of material combination have been constructed for electrostatic device using the basic structure shown in Fig. 1. Table 1 shows the material combination A, B, and C.

TABLE I. MATERIAL COMBINATION FOR ELECTROSTATIC DEVICES

Electrostatic device	Layer thickness		
	Electrode	***Dielectric***	***Cover insulator***
A	Copper 35um	Polyimide, er~3.0 50um	Polyimide 50um
B	Aluminium 24um	Polypropylene, er~2.2 90um	PVC 42um
C	Aluminium 24um	Silicone, er~2.8 220um	PVC 42um

Material combination for electrostatic device A is essentially a flexible printed circuit (FPC). Fig. 2 shows the pattern of the printed copper electrode. Material combination for electrostatic device B and C is constructed with aluminium foil (electrode), transparency film and keyboard protector (dielectric), and PVC tape (cover insulator) layers. The pattern of the electrode for material combination B and C is as shown in Fig. 1.

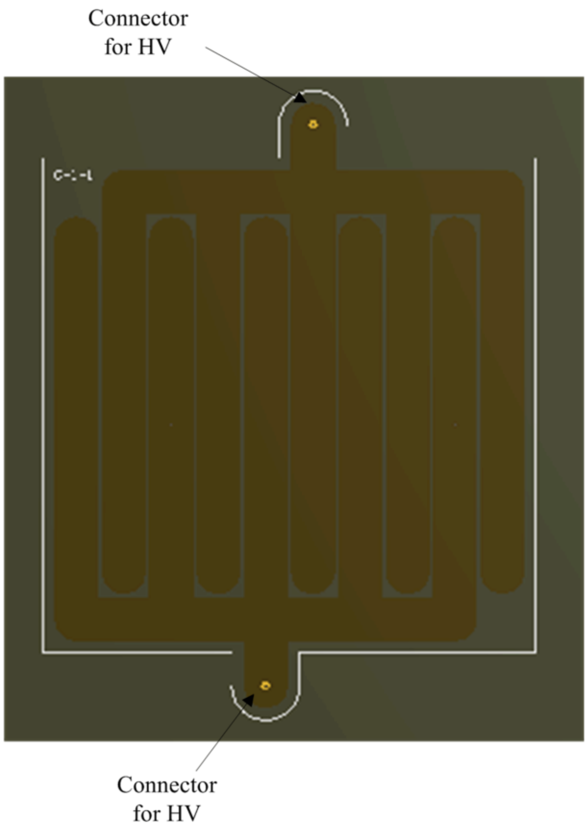

Fig. 2. Electrostatic device with interdigitated electrode pattern.

III. Results and Discussion

A. *FPC Electrostatic Device*

The fabricated FPC is named A-1-1. It was placed on top of a piece of paper, on top of workbench, as shown in Fig. 3. This made the effective separation distance to become 146um. Pull force is applied after 1 min of DC HV supply. Initially, pulling the paper laterally requires minimal effort. Once the device receives high voltage power supply, immediately the paper is “weighted” as if a normal force is push towards the bench. More lateral pull force is needed to shear the paper across the bench. The electrostatic device is said to hold the paper against externally applied shear force. At 5kV, the HV power supply is shown supplying 20uA of electrical current to device A-1-1.

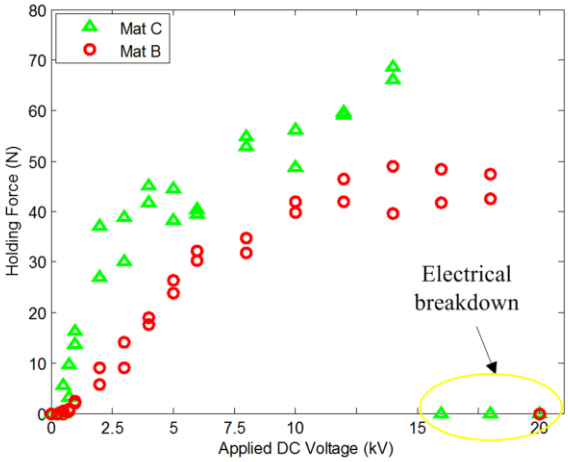

Fig. 7. Measured holding force for electrostatic devices B and C actuated on ceramic surface. The electrical breakdown are as shown.

The holding force is evaluated at different voltage level. The result is shown in Fig. 4 along with theoretical prediction using (2). Then a coefficient of 0.08 is added into (2) to obtain the fit depicted, which matches the experiment results quite well. This coefficient is to adjust the effect of modification of relative permittivity for additional paper, and also other factors such as coefficient of friction, surface roughness, and angle of pull, etc. into (2). The result also shows saturation of holding force at higher level of applied HV, which is not described by (2). The force output to device mass ratio is quite high, since A-1-1 weighs about 1.5N and is able to output 10X of holding force.

B. *Coplanar Electrostatic Device*

One usage of this electrostatic device using material combination B is shown in Fig. 5. Note that the wooden work piece depicted has a fairly rough surface and it is non-electrically conductive. Once the static charges are imaged at the work piece, removing the HV power supply does not affect the attraction of opposite bound charges. However, removing the work piece from the electrostatic device is also simple.

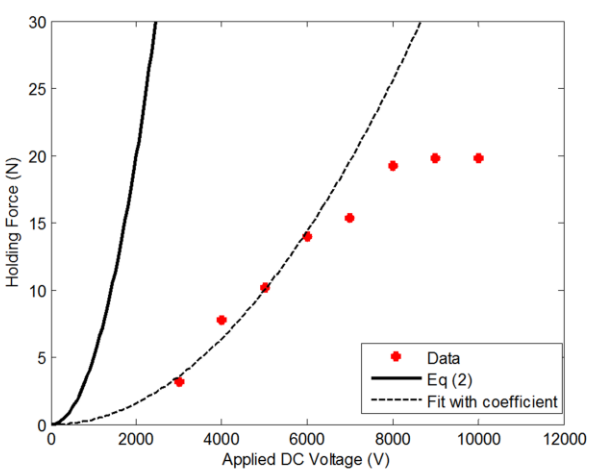

Fig. 4. A-1-1on Paper and Bench surface.

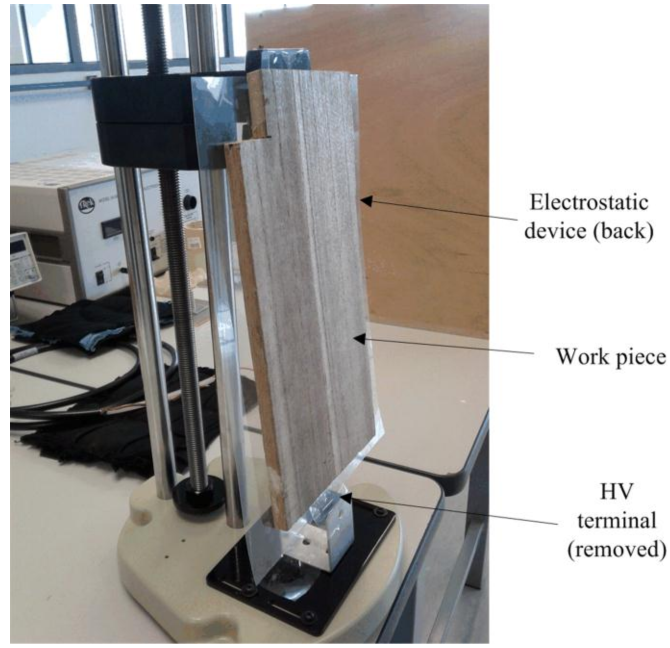

Fig. 5. Electrostatic device holding a wooden work piece, even after HV supply has been removed.

Tilting the vertical axis to beyond certain degree can readily "peel off" the work piece from the electrostatic device. This mechanism to easily attach and detach work piece is an advantage of electrostatic adhesion technique.

Qualitative results showing the electrostatic device on Ceramic surface is shown in Fig. 6. Next the electrostatic devices are also tested against Glass surface, shown in Fig. 7. The coplanar electrodes for both devices are 7 inch length and 4 inch wide. The measured holding force is an indication of applicable payload of a work piece for these electrostatic devices. Results show a quadratic relation between holding force and applied HV within the 2kV range. Beyond 2kV voltage level, the force tends to increase and saturate towards 20kV. This is not readily modelled in (2), and requires further investigation.

Finally the terminals of electrostatic device B and C are

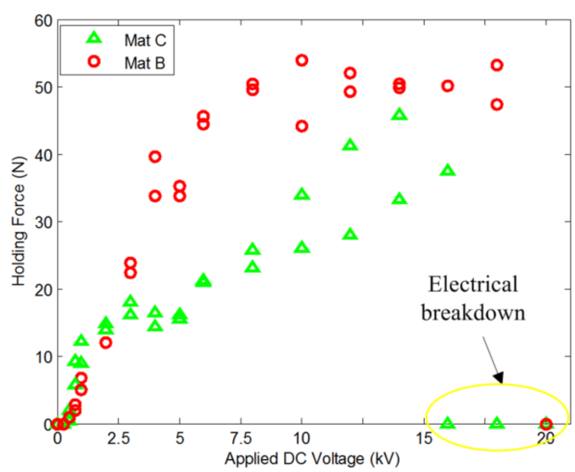

Fig. 6. Measured holding force for electrostatic devices B and C actuated on ceramic surface. The electrical breakdown are as shown.

isolated and actuated with polarised HV. The device is being supplied from -20kV to +20kV with a single HV Output without the HV Return. Even without a return path to the HV power supply, the electrostatic device is able to generate electrostatic force to hold against work piece. The results are shown in Fig. 8. It is interesting to see that positive and negative polarity yields similar level of output holding force, as if vertical mirror line existed at 0V. This result is important in the sense that in nature, static charges do not discriminate the charge polarity for object adherence. It is the magnitude of voltage level that controls the electrostatic force. Also evident from the result is the saturation nature of $F - V$ relation at higher voltage levels. Again this is not readily modelled in (2) and requires further investigation.

IV. Conclusion

Qualitative investigation on electrostatic devices for material handling is presented. These thin film devices have generated useful level of attachment force against arbitrary work pieces. The grasp and release mechanism is simple to implement, time required for attachment is short, and consumption of electrical current is low. It also works on non-conductive work piece with fairly rough surface. These confirmed advantages of electrostatic adhesion can be developed into industrial grippers. However, qualitative results have shown that only within a certain voltage level the F - V relation is quadratic as described by the parallel capacitor model. The saturation characteristic at higher voltage level requires further investigations.

Acknowledgment

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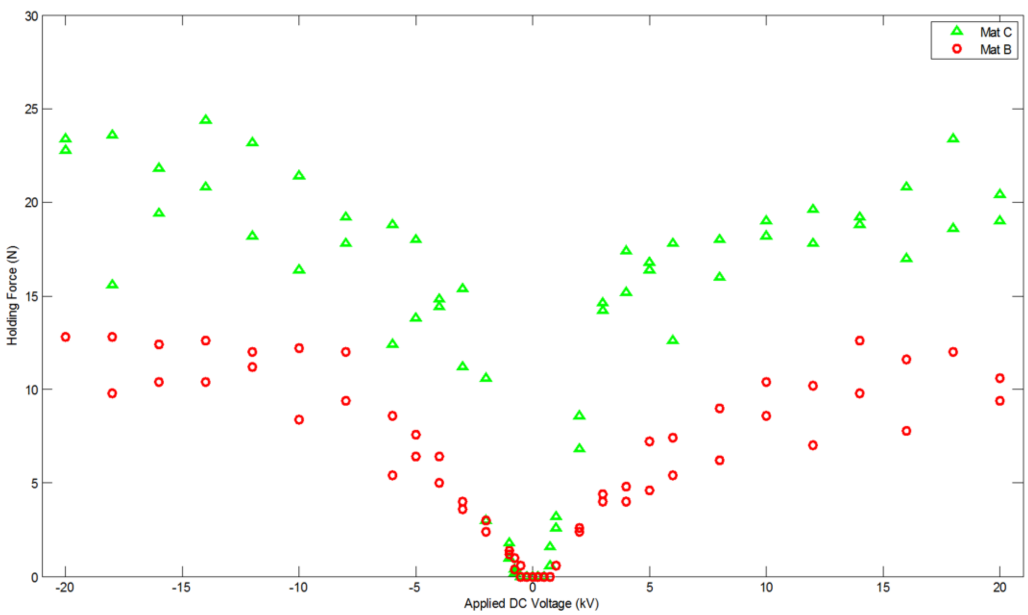

Fig. 8. Measured holding force for electrostatic devices B and C actuated on glass surface. HV supply is polarized and non-returned.

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