Regular Paper

Peel Force of Electrostatic Adhesion in Crawler-type Electrostatic Climbing Robots

Hongqiang WANG*¹ and Akio YAMAMOTO*¹

This research investigates the peel force of electrostatic adhesion, or electroadhesion, based on the Kendall model. In the other adhesive materials such as adhesive tapes, the adhesive energy density is decided only by the property of the bonding interface, and its value can only be acquired by experiments. In the electrostatic adhesion, however, because the adhesive energy is generated by electric field, it can be calculated as electric energy and controlled by changing the voltage or the layout of the electrodes. Due to the absence of interface bond in electrostatic adhesion, the adhesive energy density does not change with the peel velocity, while other types of adhesion such as adhesive tapes do. As for electrostatic crawler-type climbing robots, the paper discusses solutions to strengthen the peel torque of the robot. The paper shows that the pretension force has an optimal value for maximum peel torque.

Keywords: peel force, climbing robot, electrostatic adhesion, electroadhesion.

(Received: 24 July 2014)

1. Introduction

Electrostatic adhesion, or electroadhesion, is a promising adhesion technique with many potential applications. It can be employed, for example, in silicon wafer transportation, glass handling, and robotic gripping [1-4]. It can also be used for the adhesion of climbing robots, and many prototypes have been developed previously [5-8]. In these prototypes, the electrostatic adhesion is usually realized using thin electrode films. Examples for this kind of films are shown in Fig. 1. The films enable the electroadhesive climbing robots to save much weight compared to robots based on other adhesion methods, such as the dynamic air suction and magnetic adhesion. However, due to the flexibility of the electrode films, electroadhesive robots on a vertical wall are apt to be peeled off as shown in Fig. 2, even though the lateral electrostatic adhesion force is still strong enough to support the robot. Accordingly, the peel force limits the capability of electroadhesive climbing robots. The peel force, however, has not been extensively studied for electrostatic adhesion. To facilitate the application of electrostatic adhesion, this paper focuses on the characteristics of the peel force in electrostatic adhesion.

Although peel force of an adhesive tapes has been thoroughly investigated in the last decades, the area of the peel force of electroadhesion is still blank, which is expected to differ from the other adhesion methods in some aspects. For example, in the previous research on peel force, Kendall model was introduced and extensively used in the study of, e.g., tapes and gecko adhe-

sion [9-11]. However, it is unclear whether this model can be applied to electrostatic adhesion or not. In the peel test of tapes, the adhesive energy density in Kendall model varies with the peel speed due to the viscosity of glue and can only be obtained experimentally. On the other hand, in electrostatic adhesion, because the adhesive energy density is generated by electric field, it should be able to be theoretically calculated from the electrical energy and can be controlled by changing voltage. Considering no interface bonding exists, the electrostatic adhesive energy could be independent from the peel speed.

To clarify the above questions, this paper models the peel force of electrostatic adhesion based on Kendall model. To verify the proposed model, we experimentally investigate the peel force under different voltages, different layouts of electrodes, and different peel veloci-

Fig. 1. Principle of electrostatic adhesion with 2-phase electrodes (a) and 3-phase electrodes (b)

Fig. 2. The peeling off of a crawler-type electroadhesive climbing robot

Correspondence: H. WANG, Department of Precision Engineering, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
email: wanghqiang@aml.t.u-tokyo.ac.jp

*¹ The University of Tokyo

ties.

The paper also discusses how to strengthen peel force of crawler-type electroadhesive robots. One of the solutions can be making the belt film tighter by pretension. The paper experimentally verifies the relationship between the peel force and the pretension force strength.

The structure of this paper is as follows. The next section proposes a new model for the peel force of electroadhesion based on Kendall model, in which we calculate adhesive energy density by the electric energy. Section 3 experimentally verified the model by different conditions. Section 4 is going further to investigate the peel torque generated by the peel force on a crawler-type climbing robot. Experiments were induced to test the effects of the pretension force.

2. The peel force of electrostatic adhesion

2.1 The calculation model

There are many models to calculate the peel force of a thin adhesive film [9,10,12,13]. Among them, Kendall model is one of the most widely used ones, which was originally proposed for adhesive tapes. In this research, we extended this model to describe the peel force of electrostatic adhesion.

In Kendall model, the peel force can be calculated as, [9]

$$F_p = \frac{Rb}{1 - \cos \theta} \quad (1)$$

in which F_p is the peel force, b is the width of the film, and R is the adhesive energy density, and θ is the peel angle as shown in Fig. 3. This equation reveals that the peel force is only decided by the adhesive energy, if the peel angle is constant.

In other adhesion methods, the adhesive energy density can be obtained only through experiments. However, in electrostatic adhesion, we propose to calculate it based on the electrical energy as follows.

2.2. The electroadhesive energy density

In Kendall model, the adhesive energy density R is a critical factor in calculating the peel force. Therefore, in the following discussions, we focus on adhesive energy density and discuss how we can calculate it for electrostatic adhesion.

The simplest model for electroadhesion includes only one electrode on a conductive substrate, which is electrically grounded. Its normal adhesive force can be calculated as

$$F_{ad} = \frac{1}{2} \frac{\epsilon S_e}{d^2} V^2 \quad (2)$$

where ϵ and d are the permittivity and thickness of the dielectric layer between the electrode and the substrate respectively, S_e is the electrode area and V is the voltage. In our model, we use the electric energy stored in this system to calculate the adhesive energy density,

$$R = \frac{W_{ad}}{S_e} = \frac{1}{2} \frac{\epsilon}{d} V^2 \quad (3)$$

Usually, in practice, two-phase electrodes or three-phase electrodes are used, as shown in Fig. 1. In these configurations, the electrodes are interdigitated, so the distribution of R is not continuous. Here, we take two-phase electrodes as an example. Assuming both the width of each electrode and the space between electrodes are w , the adhesive energy density, which depends on the position x , can be calculated as,

$$R(x) = \begin{cases} \frac{W_{ad}}{S_e} = \frac{1}{2} \frac{\epsilon}{d} V^2 x \in (2kw, (2k+1)w) \\ 0 & x \in ((2k+1)w, 2(k+1)w), \end{cases} \quad k \in \mathbf{Z} \quad (4)$$

However, if the electrode film is stiff enough for bending or the electrodes are considerably thin, the interdigitally distributed energy will be averaged. This is a typical case for electrostatic adhesion and was verified in our experiments. In the later analyses, we will only consider the average adhesive energy density.

Now let us consider the adhesive energy in two configurations: 2-phase and 3-phase electrode films, which are usually used in electroadhesive climbing robots. [5-8]

(1) Two-phase electrode film

Electroadhesion can be achieved either by applying DC or AC voltages. When two polarity-inversed DC voltages (+V, -V) are supplied to the electrodes as shown in Fig. 1 (a), the average adhesive energy density is calculated as

$$\bar{R} = \frac{1}{2} \frac{\epsilon}{d} \frac{1}{4S_e} (S_e V^2 + S_e (-V)^2) = \frac{1}{4} \frac{\epsilon}{d} V^2 \quad (5)$$

If supplying a two-phase AC voltage, we have

$$\begin{aligned} \bar{R} &= \frac{1}{2} \frac{\epsilon}{d} \frac{1}{4S_e} (S_e V^2 \sin^2 \omega t + S_e V^2 \sin^2(\omega t + \pi)) \\ &= \frac{1}{8} \frac{\epsilon}{d} V^2 (1 - \cos 2\omega t) \end{aligned} \quad (6)$$

where ω is the angular frequency, and t is the time. This equation reveals that the peel force vibrates with the two times of the voltage frequency, when AC voltage is used.

(2) Three-phase electrode film

When we supply a DC voltage (V, 0, -V) to 3-phase electrodes shown in Fig. 1(b), we have

$$\bar{R} = \frac{1}{2} \frac{\epsilon}{d} \frac{S_e}{6S_e} (V^2 + 0^2 + (-V)^2) = \frac{1}{6} \frac{\epsilon}{d} V^2 \quad (7)$$

On the other hand, if we supply the electrodes with a 3-phase AC voltage, the average adhesive energy is

Fig. 3. Kendall model on peel force

Fig. 4. The electrode films used in the experiments

Fig. 5. The experiment setup for peel test including its appearance (a), the working mechanism (b) and the top view (c)

$$\begin{aligned} \bar{R} &= \frac{1}{2} \frac{\varepsilon}{d} \frac{S_e}{6S_e} V^2 (\sin^2 \omega t + \sin^2 (\omega t - \frac{2\pi}{3}) \\ &\quad + \sin^2 (\omega t + \frac{2\pi}{3})) = \frac{1}{8} \frac{\varepsilon}{d} V^2 \end{aligned} \quad (8)$$

The right-hand side of the equation does not contain the frequency component, which means it does not vibrate although AC voltage is supplied. This is different from the case of 2-phase electrode with AC excitation.

3. Experiments and Discussions

To verify the analyses above, we measured the peel force under three situations: on 2-phase electrode, on 3-phase electrodes and on plane electrodes. Hence two configurations of electrode films, as shown in Fig. 4, were used in the tests. In film A, the electrodes are arranged in six phases. We can connect the phases of (1, 3 and 5), as well as (2, 4 and 6) to make it work as a 2-phase electrodes. We can also connect (1 and 4), (2 and 5) and (3 and 6) separately to use it as a 3-phase electrode film. Film A was made by screen printing. Its base layer was made from polyimide. The thickness and relative permittivity of the base layer are 25 μm and 3.4 respectively. The electrodes were printed on the base layer using silver paste. On top of the film, a layer of resin was covered on. The whole thickness of the film is 70 μm . On the other hand, film B has two large plane

 Fig. 6. The force achieved by the force sensor in the peeling processes (a) and the corresponding peel force (b) (on film A; peel speed: 115 $\mu\text{m/s}$; voltage: 3-phase 500 V DC)

 Fig. 7. The peel force as 3-phase AC voltage is supplied ((on film A; peel speed: 115 $\mu\text{m/s}$; voltage: 500 V))

Fig. 8. The peel force in the 3-phase electrode film (on film A; peel speed: 115 $\mu\text{m/s}$; voltage: 3-phase AC/DC)

Fig. 9. The peel force in the 2-phase electrode film (on film A; peel speed: 115 $\mu\text{m/s}$; voltage: 2-phase AC/DC)

Fig. 10. The peel force in the 2-phase electrode film (on film A; peel speed: 115 $\mu\text{m/s}$; voltage: 500 V 2-phase AC)

electrodes. The electrodes, made of aluminum foils, were attached to a polyimide layer of 25- μm thickness. The thickness of film B is 120 μm . We are mainly interested in the peel force of interdigital electrodes, so film A was mostly used in the tests. The film with plane electrodes (film B) was used to verify the analysis as another example.

The experimental setup to test the peel force is shown in Fig. 5. A film was located on a horizontal aluminum board, which was electrically grounded. One edge of the film was connected to a force sensor, which was supported by a linear slider on a 45° slope, such that the film can be peeled in the angle of 90°. In the peel test, the sensor was either driven by a linear motor

or moved by hands. A laser displacement sensor was located nearby to record the position of the force sensor.

In the peel test, because the peel force is considerably weak, film's weight cannot be neglected. To eliminate the effect of film's weight, we took three steps. In the first step, we set the output value of the force sensor at the starting point as zero. We moved the force sensor to "peel" the electrode film, not supplying voltage. One example of the result is shown in Fig. 6 in black. The value is the incremental weight (ΔF_g) of the film pulled up by the force sensor. In the second step, we repeated to peel the film as the first step but supplying voltage in this case. The obtained value was the sum of the peel force and the incremental weight of the film ($F_p + \Delta F_g$). Finally by subtracting the value of step 1 from that of step 2, we obtained the peel force, as shown in Fig. 6(b). In every peel test, the peel distance was 17 mm due to the limitation of the motor's stroke.

3.1. Experiments with interdigital electrodes (film A)

3.1.1 Voltage dependence

To study the effects of voltage on the peel force, we investigated both DC and AC, as well as 2-phase and 3-phase using film A. The peel force fluctuated during the peel process due to the imperfection of the contact surface, as shown in Fig. 6(b). We took the average value of the peel force in the whole peeling process as the characteristic value for the corresponding condition. The average peel forces under different conditions are shown in Figs. 7-10. The tested results in all of these situations are coincident with the estimation based on the analyses above.

In the 3-phase electrode film, the peel force did not vibrate with the voltage frequency in both AC and DC conditions, agreeing with the estimation. Sometime, under AC voltage, a small vibration was observed, but the reason is still unclear.

In the 2-phase electrode film, the peel force vibrated at the two times of the voltage frequency, just as estimated. When 600 V AC or DC voltage was supplied, the peel force was not as high as estimated, as shown in Fig. 9. This probably resulted from the corona discharge, because in the tests, we heard hiss noise at this voltage, which is an indication of corona discharge. As a comparison, in 3-phase electrode the corona discharge did not happen, which may be due to the voltage difference between nearby electrodes are higher in 2-phase electrodes. Also in DC condition, the force degradation was more distinct than AC. This is probably due to the current flowing through the surface of the insulator. As the charges flow and accumulate on the surface, the electric field is shielded, which weakens the electrostatic force. In fact, a similar phenomenon was reported in electrostatic film motors [14].

3.1.2 Peel velocity dependence

In the previous research on peel force of adhesive tapes, R varies with the peel speed due to the viscosity

Fig. 11. The effect of peel speed on adhesive energy density of electroadhesion (on film A; voltage: 500 V 3-phase DC)

Fig. 12. The peel force on film B (peel speed: 115 µm/s; voltage: 2-phase DC)

of the interfacial bonds (such as glue) [9,13]. However, because electrostatic adhesion is not caused by the interface bond but by the electrostatic force, the peel velocity should not affect R . To verify this, we peeled film A using the peel testing device mentioned above under different velocities. The peel velocities lower than 115 µm/s were achieved by controlling the speed of the linear motor. The speeds higher than that value were realized by moving the force sensor manually. As shown in Fig. 11, the adhesive energy density of electroadhesion did not show any dependence on velocity in the range from 0.021 mm/s to 11.3 mm/s.

3.2. Peel force on the film with plane electrodes (film B)

To further verify the analysis, we measured peel force using film B, which has different materials and structure from film A. Differently from film A, deformation of the electrodes was observed, due to its manufacturing process. The deformation creates some air gaps between the electrode and the base film, and thus the gap between the electrode and the substrate was not equal to the thickness of the base layer. To estimate the effective gap, first we tested the lateral adhesive force by pulling film B on the aluminum board. With the predetermined friction coefficient, the normal adhesive force and, in turn, the effective gap was estimated according to Eq. 2. The estimated gap was 61 µm for this specific case.

Two polarity-inversed DC voltages were applied to the electrodes of film B and peel force was measured. The measured results were in good accordance with the estimated results using this effective gap, as shown in

Fig. 12. On 600 V DC, the tested result is higher than the estimation. This is probably because at this voltage, the adhesive force became strong enough to reduce the electrode deformation and thus decreases the effective gap between electrodes and the substrate.

4. Peel force of electroadhesive climbing robot

4.1. The torque balance of crawler-type climbing robot

The peeling off of the crawler-type climbing robot on a vertical wall happens when the torque balance of the robot body is broken as shown in Fig. 13(a). Therefore we can mainly consider the torque caused by the peel force for the balance of the robot. Assuming the rotating angle of the robot body is considerably small, it can be calculated as,

$$M_p = F_p \sin \theta l_p = \frac{Rb}{\tan(\theta/2)} l_p \quad (9)$$

where the l_p is the length between the peel force acting point on the robot body and the rotating center. Accordingly, to strengthen the peel torque, there are two possible solutions. One is to increase the adhesive energy density by increasing the voltage. The other way is to reduce the peel angle. This can be realized by tightening the belt film, which is verified in the following experiments.

For easy testing, we consider another similar situation on a horizontal plane as shown in Fig. 13(b). Here a

Fig. 13. The torque balance on a crawler-type electrostatic adhesive climbing robot

Fig. 14. The experimental setup for testing the peel force of the crawler-type climbing robot

Fig. 15. The effect of pretension force on the peel torque (pulling speed: 115 $\mu\text{m/s}$; voltage: 500 V 3-phase DC)

torque generated by the force P balances with the torques from peel force and the gravity force,

$$Pl = M_p + M_g \quad (10)$$

where l is the length between the pulling point on the robot to the rotating center, and M_p and M_g are the peel and gravity torques respectively.

4.2. Experiments with different pre-tension

To test the peel torque of a crawler-type climbing robot, we made the experimental setup shown in Fig. 14. A crawler-robot like prototype was pulled up by a force sensor (force sensor 1) which is driven by a linear motor. The moving distance of this force sensor was 17 mm. In the prototype, two plastic rollers were fixed by bolts on the front and back edges. A force sensor (force sensor 2) connected to the belt film was placed on the main body to measure the pretension force. Two bolts were used to adjust the pretension force. The electrode film was made from a piece of film A.

In the experiment, we pulled force sensor 1 under two conditions. In one condition, voltage (500 V, 3-phase DC) was applied to the electrodes, whereas in the other condition, no voltage was applied to measure the gravitational torque. The tested peel torque under different pretension force is shown in Fig. 15. Just as expected by Eq. 9, the peel torque increased as tension force increased. However, as the film was stretched too much, the intimate contact between the electrode film and the substrate was probably deteriorated, which resulted in lowering of the peel force. The optimal tension force for this prototype was found around 3.5 N and the maximum peel torque was 0.055 Nm.

5. Conclusions

This paper analyzed the peel force of electrostatic adhesion using Kendall model, in which the adhesive energy density R was calculated by the electrical energy. In electrostatic adhesion, the adhesive energy density can be controlled by changing the electrode layout and voltages, but it is not affected by the peel velocity. These characteristics are different from the other adhesion methods such as tapes, the adhesion energy of which cannot be changed arbitrarily and increases as the peel velocity becomes faster. In the electroadhesive

climbing robot, we found that the pretension force can increase the peel torque, but too-high tension force will deteriorate the adhesive energy as well as the peel torque because more air gaps are generated. An optimal value of pretension force for the maximum peel torque exists.

References

- [1] A. G. Wardly, "Electrostatic Wafer Chuck for Electron Beam Microfabrication," *Review of Scientific Instruments*, Vol.44, No.10, pp.1506-1509, 1973.
- [2] R. Müller, et al, "Super-Flat Wafer Chucks: from Simulation and Testing to a Complete 300mm Wafer Chuck with Low Wafer Deformation Between Pins," *SPIE Advanced Lithography. International Society for Optics and Photonics*, pp.90482E-90482E-7, 2014.
- [3] R. Moser; R. Wuthrich; L. Sache; T. Higuchi; H. leuler, "Characterization of Electrostatic Glass Actuators," *J. Appl. Phys*, Vol.93, pp.8945-8951, 2003.
- [4] M. Boudaoud, Y. Haddab, Y. G. Le. "Modeling and Optimal Force Control of a Nonlinear Electrostatic Microgripper," *Mechatronics, IEEE/ASME Transactions on*, Vol.18, No.3, pp.1130-1139, 2013.
- [5] A. Yamamoto, T. Nakashima, T. Higuchi, "Wall Climbing Mechanisms Using Electrostatic Attraction Generated by Flexible Electrodes," *Proc. 2007 IEEE International Symposium on Micro-NanoMechatronics and Human Science*. Pp.389-394.
- [6] H. Prahlad, R. Pelrine, S. Stanford, et al. "Electro-adhesive Robots—wall Climbing Robots Enabled by a Novel, Robust, and Electrically Controllable Adhesion Technology," *Proc. 2008. IEEE International Conference on Robotics and Automation*, pp.3028-3033, 2008.
- [7] H. Wang, Akio Yamamoto, and T. Higuchi. "Electrostatic-motor-driven electroadhesive robot," *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. IEEE, pp.914-919, 2012.
- [8] H. Wang, and A. Yamamoto, "A Thin Electroadhesive Inchworm Climbing Robot Driven by an Electrostatic Film Actuator for Inspection in a Narrow Gap," *Safety, Security, and Rescue Robotics (SSRR), 2013 IEEE International Symposium on*. IEEE, pp.1-6, 2013.
- [9] K. Kendall, "Thin-film Peeling—the Elastic Term," *Journal of Physics D: Applied Physics*, Vol.8, No.13, pp.1449-1452, 1975.
- [10] K. L. Johnson, K. Kendall, A. D. Roberts. "Surface Energy and the Contact of Elastic Solids," *Proceedings of the royal society of London. A. mathematical and physical sciences*, Vol.324, No.1558, pp.301-313, 1971.
- [11] B. Chen, P. Wu, H. Gao. "Pre-tension Generates Strongly Reversible Adhesion Of A Spatula Pad On Substrate," *Journal of The Royal Society Interface*, Vol.6, No.35, pp 529-537, 2009.
- [12] N. S. Pesika, Y. Tian, B. Zhao, et al. "Peel-zone Model of Tape Peeling based on the Gecko Adhesive System," *The Journal of Adhesion*, Vol. 83, No. 4, pp. 383-401, 2007.
- [13] M. Zhou, et al. "The Extended Peel Zone Model: Effect of Peeling Velocity," *The Journal of Adhesion*, Vol.87, No.11, pp.1045-1058, 2011.
- [14] T. Hosobata, A. Yamamoto, T. Higuchi, "An Electrostatic Induction Motor Utilizing Electrical Resonance for Torque Enhancement," *Sensors and Actuators A: Physical*, Vol.173, No.1, pp.180-189, 2012.