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Rapid de-electroadhesion with exponential decay alternating voltages

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***Abstract*—Due to the existence of residual charges, electroadhesion usually suffers from slow de-electroadhesion (in the range of several minutes to hours), significantly limiting its application in handling lightweight objects. To date, mechanical push or vibration is the main solution to achieve rapid de-electroadhesion, resulting in the complexity and inefficiency of electroadhesive devices. Inversely charging provides an ideal solution, but the voltage form remains elusive. In this work, we report an electrical solution that can achieve rapid de-electroadhesion by applying a programmable exponential decay alternative voltage. We investigate the influence of voltage parameters (including the decay factor, lasting time, and the number of alternations) on de-electroadhesion time. The results reveal that the de-electroadhesion time can be reduced by decreasing the decay factor and lasting time and increasing the number of alternations. The experimental results of different substrates (regular paper, copper, and kraft paper) demonstrate that our method can achieve fast release of the electroadhesion and the release time can be reduced by three orders, verifying the effectiveness of the electrically controlled rapid de-electroadhesion method.**

***Index Terms*—Electroadhesion, rapid de-electroadhesion, exponential decay alternating voltages, parameter optimization.**

I. Introduction

ELECTROADHESION is a promising controllable adhesion technology due to its increased adaptability, reduced complexity, low energy consumption (in the range of μA-mA), and gentle contacts with various materials [1]. In general, an electroadhesive pad consists of parallel or coplanar electrodes embedded into dielectric materials. When a high voltage is applied, the anode and cathode of the electroadhesive pad accumulate positive and negative charges, respectively. At the same time, the substrate generates opposite charges because of the polarization or electric induction, depending on the electrical property of the substrate. The electrostatic attraction between those charges generates electroadhesive force [2], [3]. Based on the working principle, different kinds of electroadhesive devices have been well developed, which have been widely used for robotic gripping [4]–[7], locomotion [8]–[12], and haptics [13].

However, the controllability of the electroadhesion is limited by the fact that the electroadhesion is a dynamic electrostatic attractive effect, meaning that it takes a finite amount of time for the maximum electroadhesive force to be produced after one applies a voltage to the electroadhesive device (called electroadhesion) and the adhesive force to diminish after one turns off the voltage (called de-electroadhesion) [14]. This is due to the dynamic polarization during the adhesion process and de-polarization during the de-electroadhesion process. As a result, electroadhesion can lift lightweight objects with a high response speed, but de-electroadhesion of lightweight objects may take minutes or hours, depending on the weights and properties of the objects. This has been motivating the development of reliable and rapid de-electroadhesion solutions.

To date, the commonly used methods are the mechanical solutions that can accelerate the de-electroadhesion by applying a mechanical force. In general, mechanical solutions can be divided into push methods (such as the use of pegs, air jets, and pneumatic inflations) and vibration methods (such as the use of piezoelectric vibrations and dielectric elastomer actuated vibrations). In terms of push methods, Monkman proposed the use of plastic pegs and air jets to remove materials beneath the electroadhesive device through small holes [15]. Xiang et al. employed a pneumatic inflation method to facilitate rapid de-electroadhesion of a soft electroadhesive pad [16]. In terms of vibration methods, Monkman applied small piezoelectric actuators behind the electroadhesive pad to produce small vibrations to eject the object in a controlled manner [17]. Gao et al. combined a dielectric elastomer actuator with a soft electroadhesive pad and developed a rapid de-electroadhesion method by exploiting the resonant vibration of the dielectric elastomer actuator [18]. In addition, Cacucciolo et al. developed a rapid de-electroadhesion method by controlling the peeling angle [19]. Mechanical solutions are straightforward and reliably rapid, but they tend to make the electroadhesion system complex by adding additional drives or manufacturing through-holes in the electroadhesive pad.

Different from mechanical solutions, applying polarity reversing voltage to mitigate the residual charges can significantly simplify electroadhesive end effector structure and improve efficiency, which is more desirable. However, due to the uncertainty of the residual charges (that highly depends on the voltage, substrate, environment, and so on), the polarity reversing voltage easily leads to overcharge, generating

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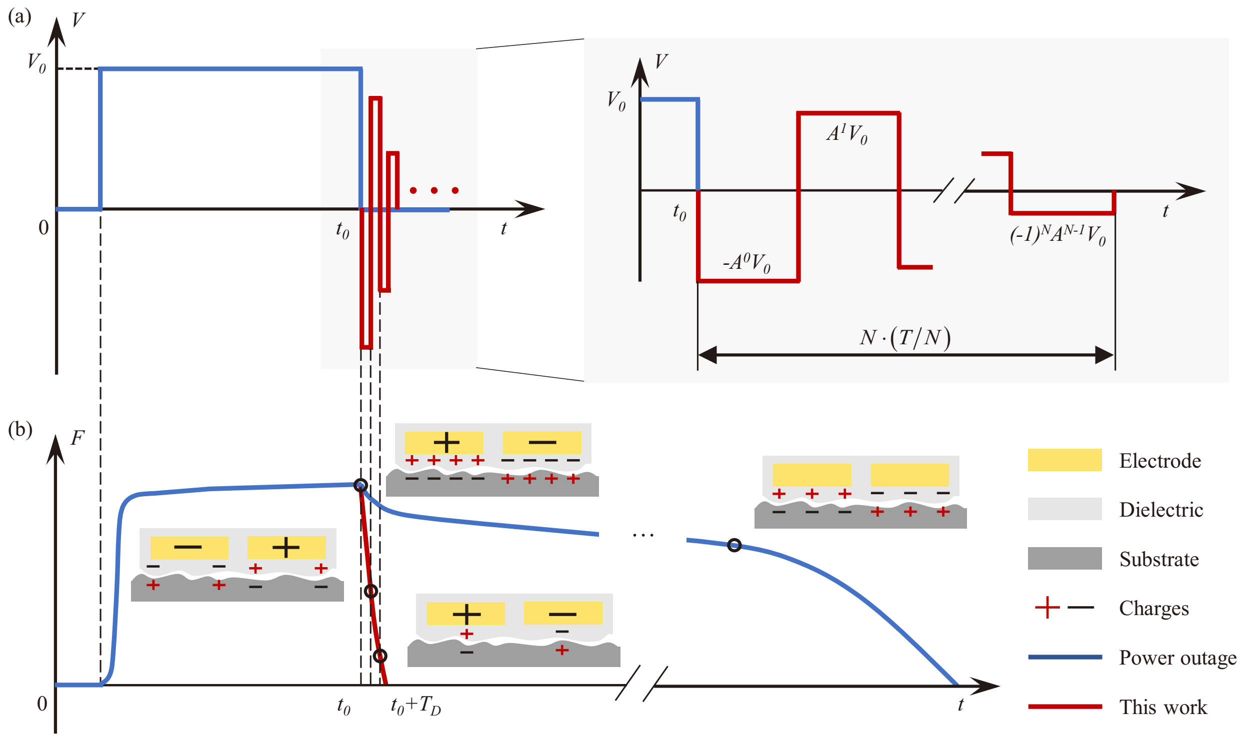

Fig. 1. Comparison between regular and rapid electrical de-electroadhesion. (a) Voltage application strategies; (b) Dynamic electroadhesive forces.

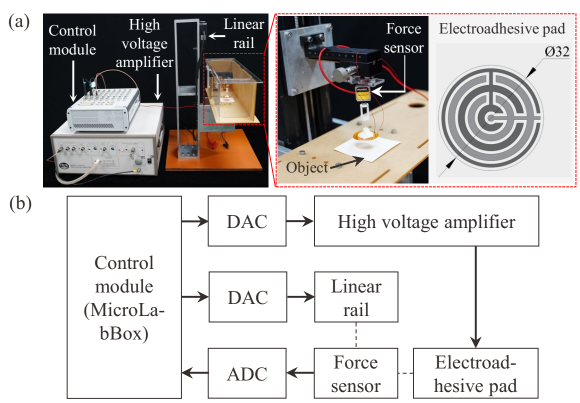

Fig. 2. The experimental platform. (a) Experimental setup; (b) Block diagram.

new electroadhesion force. In previous literature, only a few research papers have briefly mentioned the electrical de-electroadhesion methods. For example, Brecher et al. proposed the use of potential inverting whilst reducing the amplitude of the voltage multiple times to achieve a defined reduction of attractive forces for reliable and rapid de-electroadhesion [20]. In addition, some patents [21], [22] also provide some concepts about the electrically controlled rapid de-electroadhesion method, but experimental verification is absent. Therefore, the specific voltage form of the electrically controlled rapid de-electroadhesion methods still remains elusive, significantly limiting their practical applications.

To overcome the drawback of existing de-electroadhesion methods, this work aims to propose an electrically controlled approach to achieve rapid de-electroadhesion. Considering the square wave can accelerate the charging and discharging process that is highly desired to rapidly eliminate the residual charges, we first design the exponential decay alternating voltage based on the square wave. We introduce the working principle of the electrically controlled rapid de-electroadhesion method. Then, the experimental setup and process are presented. Lastly, we investigate the influence of the exponential decay alternative voltage with different parameters (including the decay factor, lasting time, and the number of alternations) on the de-electroadhesion time. The experimental results of different materials demonstrate the effectiveness of our electrically controlled rapid de-electroadhesion method.

II. Working Principle

As we discussed above, the working process of the electroadhesive pad usually involves electroadhesion and de-electroadhesion, as shown in Fig. 1. During the electroadhesion, a high voltage (such as a step voltage, the blue line in Fig. 1a) is applied to the electroadhesive pad. The electrodes accumulate a number of positive and negative charges while the object generates opposite charges. The electrostatic attraction between those charges forms electroadhesive force F (Fig. 1b). In general, F can rapidly increase in a short time and then reach saturation, which can be used to lift the object. When we want to release the object at the time point of t_0, the electroadhesive pad needs to achieve de-electroadhesion. The regular method is to directly switch off the input voltage. Due to the residual charges, the electroadhesive force will not immediately diminish, making the de-electroadhesion of lightweight objects time-consuming (Fig. 1b, blue line). To accelerate the de-electroadhesion process, the key is to mitigate the residual charges. In general, the most straightforward method is to apply a polarity-reversing voltage. However, many factors (such as voltage, substrate, environment, and so on) influence the residual charges. There is still a lack of effective methods to evaluate the residual charges. As a result, it is difficult to figure out the accurate amplitude and lasting time of the polarity reversing voltage that can exactly remove the residual charges. It is easy to be overcharged, generating new residual charges. We assume that by properly selecting the amplitude and lasting time of the polarity reversing voltage, new residual charges are reverse polarity but less than the original residual charges. To further eliminate the new residual charges, we can apply another polarity reversing voltage with a smaller amplitude. By repeating the above process, the residual charges can be mitigated step by step and F can be rapidly decreased (Fig. 1b, red line), achieving rapid de-electroadhesion at the time point of $t_0 + T_D$. Based on this working principle, we design one kind of exponential decay alternating voltages (Fig. 1a, red line) that can be expressed as:

$$V(t) = (-1)^i A^{i-1} V_0, \quad t_0 + \tfrac{i-1}{N}T < t \le t_0 + \tfrac{i}{N}T \tag{1}$$

where V_0 is the original input step voltage, $i = 1, 2, \cdots, N$. We can see that $V(t)$ contains three main parameters, including the decay factor A, lasting time T, and the number of alternations N.

Remark: We would like to mention that the exponential decay alternating voltage is based on a square wave. The main reason is that the square wave can achieve faster charging and discharging speed, compared with sine wave or triangle wave. Of course, the selection of the voltage is not unique, but it may lead to an increase of the de-electroadhesion time.

The lag time between t_0 and $t_0 + T_D$ is defined as de-electroadheison time T_D that can be written as:

$$T_D = f(A, T, N) \tag{2}$$

where f is an unknown function that may depend on many different factors, such as electroadhesive device design, substrate property, environment, and so on.

Remark: It should be mentioned that electroadhesion and de-electroadhesion are a kind of complex dynamic process that involves about 33 parameters [23], including voltages, materials, interface, and environments. It still faces huge challenges to theoretically describe the charging or discharging process of the electroadhesive pad. To avoid a complex modeling process, we directly adopt an experimental approach to investigate the electrically controlled rapid de-electroadhesion method in this work.

III. Characterization of De-Electroadhesion

To this end, we establish an experimental setup (Fig. 2), which mainly consists of a linear rail, a force sensor (LSB 200, range of 10 g, max error of 0.01 g, FUTEK, USA), a high voltage amplifier (Trek 10/10B-HS, fixed gain of 1000, TREK, USA), a control module (MicroLabBox, 16 Bit ADC, 16 Bit DAC, dSPACE, Germany), an electroadhesive pad and a lightweight grabbing object. The electroadhesive pad with a pair of coplanar electrodes is used for proof-of-concept testing. The high voltage amplifier is utilized to provide programmable high voltage to the electroadhesive pad. The force sensor is used to record the weight change during the experiment which also connects the linear rail and the electroadhesive pad. The linear rail is utilized to lift the electroadhesive pad. The control module is employed to generate control signals for the linear rail and the high voltage amplifier and capture real-time signals from the force sensor. The grabbing object is made of a square piece of regular paper (side length of 60 mm and weight of 0.90 g). Considering that temperature and humidity have an influence on the electroadhesion, the whole experiments are conducted under a controlled environmental condition (30 degrees Celsius and 20% relative humidity). In addition, the force sensor, the electroadhesive pad, and the grabbing object are installed in a customized box to avoid the influence of wind. The sampling rate is set as 40 kHz.

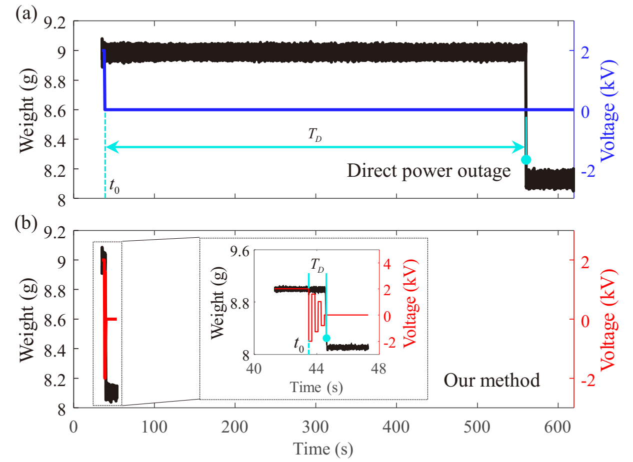

Fig. 3. Examples of the force curve under different conditions. (a) Direct power outage; (b) Exponential decay alternating voltages.

Based on the experimental setup, the characterization of T_D mainly involves the following steps:

i) In the initial state, the electroadhesive pad and the object maintain contact without input voltage.

ii) 0 s - 3 s: a step voltage (V_0 = 2 kV) is applied to the electroadhesive pad, generating electroadhesive force between the electroadhesive pad and the object.

iii) 3 s - 40.5 s: the step voltage remains constant while the linear rail is actuated to lift the electroadhesive pad with the object 15 mm up (at a speed of 0.4 mm/s).

iv) Wait for 3 s to stabilize the electroadhesive pad and then an exponential decay alternating voltage or a direct power outage is applied to the electroadhesive pad.

v) Based on the force curve during the whole process, the T_D is deduced by finding the time-point of de-electroadhesion.

Fig. 3 shows two examples of the force curve when the direct power outage and the exponential decay alternating voltage are applied to the electroadhesive pad, respectively. It can be seen that there is suddenly a force change after de-electroadhesion in both methods. Therefore, we can find the

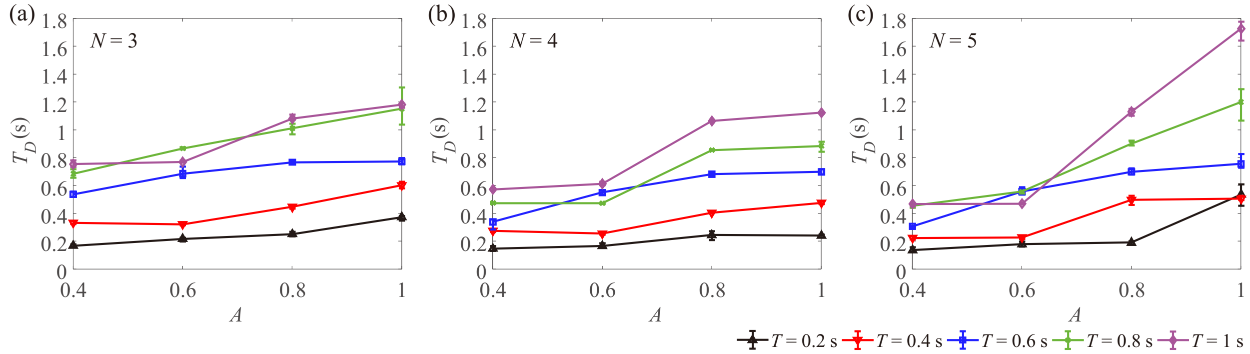

Fig. 4. The relationship between T_D and A under different N: (a) N = 3; (b) N = 4; (c) N = 5.

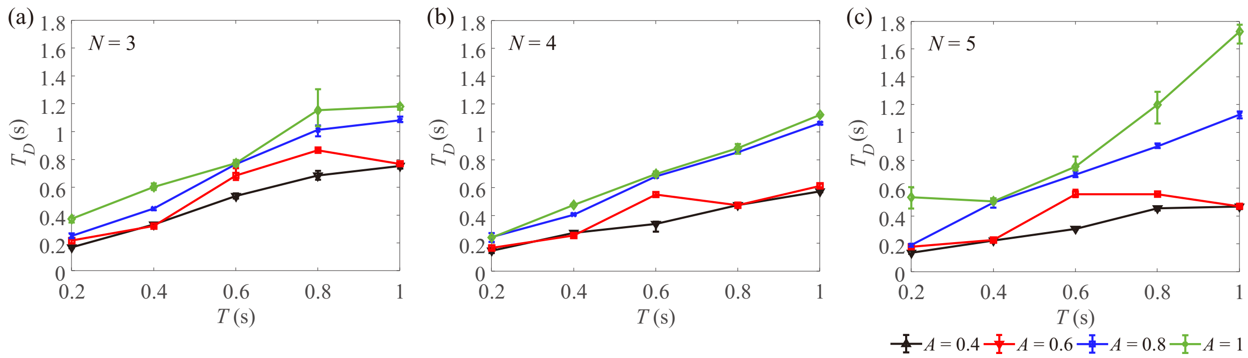

Fig. 5. The relationship between T_D and T under different N: (a) N = 3; (b) N = 4; (c) N = 5.

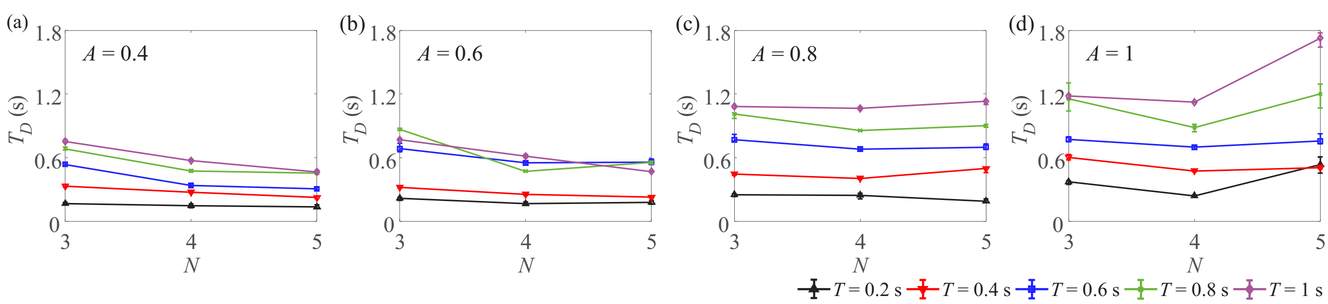

Fig. 6. The relationship between T_D and N under different A: (a) A = 0.4; (b) A = 0.6; (c) A = 0.8; (d) A = 1.

TABLE I
THE SELECTED PARAMETERS.

Parameters	Values
A	0.4, 0.6, 0.8, 1.0
$T(s)$	0.2, 0.4, 0.6, 0.8, 1.0
N	3, 4, 5

timepoint of de-electroadhesion based on the force change. To characterize the T_D, we first select the t_0 as 43.5 s in this work. For the $t_0 + T_D$, we set it as the time-point when the decrease of the force curve reaches 95% (0.86 g), avoiding the influence of the noise. Then, we can get T_D by calculating the time lag. Lastly, in order to avoid random errors, T_D is the average value of five effective tests, and the standard deviation is less than 10%.

Based on the above method, we first calculate the T_D when the input voltage is directly switched off (direct power outage, Fig. 3a). The experimental data demonstrates that the average de-electroadhesion time T_D is about 480 s with a relative standard deviation of 8.72%, seriously limiting the efficiency of the electroadhesive pad for manipulating lightweight objects.

In addition, we also characterize the T_D when the short-circuiting is adopted to achieve de-electroadhesion. The experimental results demonstrate that its average de-electroadhesion time T_D reaches about 378 s with a relative standard deviation of 9.99%. Therefore, compared with the direct power outage, the short-circuiting can decrease T_D, but it still needs a long time to achieve de-electroadhesion, limiting its practical applications.

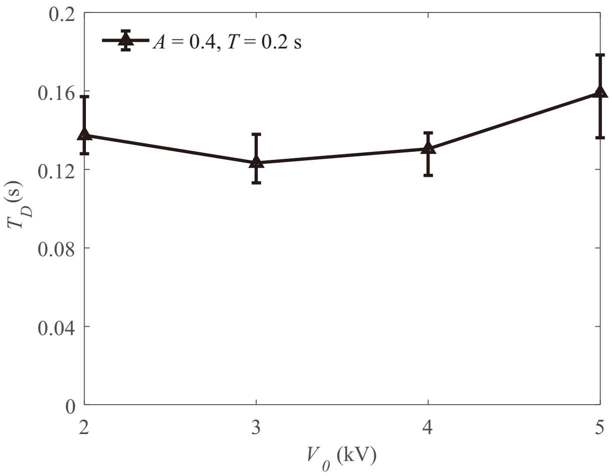

Fig. 7. The relationship between T_D and V_0.

Then, we further investigate T_D with our exponential decay alternative voltage (Fig. 3b). As shown in Fig. 1, T_D mainly relies on the three parameters of the exponential decay alternative voltage. Based on a trial-and-error method, we find the proper boundaries of those parameters that can achieve rapid de-electroadhesion. To optimize those parameters, we select four groups of A, five groups of T, and three groups of N (listed in Table I) and conduct sixty ($4 \times 5 \times 3$) groups of experiments. The experimental results are illustrated below.

Fig. 4 shows the influence of A on T_D under different N. We can see that T_D basically increases with the increase of A. This mainly depends on the fact that increasing A means a larger amplitude of the polarity reversing voltage, leading to an overcharge of the electroadhesive pad. Therefore, the decrease of residual charges becomes slower, resulting in the increase of T_D. Further, T_D is also plotted as a function of T (Fig. 5). It can be observed that T_D basically increases with the increase of T. Similar to A, larger T also means longer charging time, resulting in a slower decrease of the residual charges and an increase of T_D. Therefore, to achieve more rapid de-electroadhesion, the exponential decay alternative voltage needs to fast decay within a short time.

Remark: It should be noted that when A equals 1, the amplitude of the alternative voltage remains constant. Consequently, the electroadhesive pad is repeatedly charged and discharged, forming a changing electroadhesion force. As a result, fast alternation of the voltage may lead to mechanical vibration that can achieve de-electroadhesion with a longer T_D.

In addition, T_D also is plotted as a function of N (Fig. 6), which demonstrates that: i) when A equals 0.4 and 0.6, T_D decreases with increase of N (Fig. 6a and b); ii) when A equals 0.8, T_D basically keeps constant under different N (Fig. 6c); iii) when A equals to 1, T_D first decreases and then increases (Fig. 6d). The increasing N means lesser charging time, contributing to reducing overcharging. In contrast, larger A leads to an increase of residual charges (Fig. 4). Therefore, when A is relatively small, T_D slowly decreases with the increase of N. When A reaches about 0.8, the influences of increasing A and N are counteracted by each other, resulting in basically constant T_D under different N. Once the A equals 1, the amplitude of the inverse polarity voltage keeps constant. T_D mainly depends on the charging time: longer charging time leads to more serious overcharging while lesser charging time can not fully mitigate the residual charges. Considering that the charging time is inversely proportional to N, we can get smaller T_D when N equals a certain value (N = 4 in this work).

Remark: It should be noted that the selection of N is

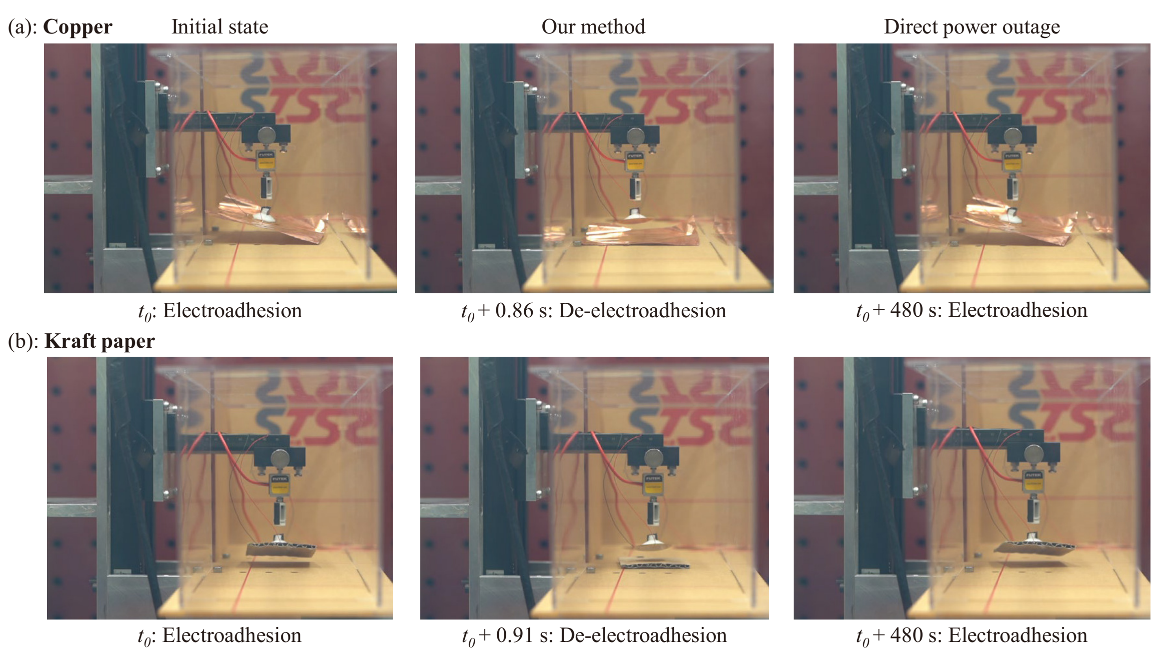

Fig. 8. Comparison between our method and direct power outage with: (a) copper; (b) kraft paper.

based on a trial-and-error method. When N equals 2, the electroadhesive pad usually suffers failed de-electroadhesion. In addition, a further increase of N may not contribute to a decrease of de-electroadhesion time because it still needs a certain time to charge or discharge.

Based on the above analysis, it can be seen that T_D can be reduced to 0.137 s when A, T, and N equal 0.4, 0.2 s, and 5, respectively. Compared with the direct power outage (about 480 s), our approach can significantly accelerate the de-electroadhesion process by 3500 times. In order to further verify the effectiveness, T_D with the optimized parameters A, T, N but different amplitudes of the original input voltage V_0 are characterized. The experimental results (Fig. 7) demonstrate that the T_D is basically independent of the amplitude of the V_0. This phenomenon can be explained as follows. The electroadhesive pad can be treated as a capacitance, whose charges are proportional to the amplitude of the V_0. Considering the fact that the exponential decay alternative voltage is also proportional to the V_0, the proper parameters of the exponential decay alternative voltage will not be influenced by the V_0.

Further, we adopt two more substrates (copper and kraft paper) to further demonstrate the generality of the electrically controlled rapid de-electroadhesion method. As shown in Fig. 8 and Movie 1, for the copper (weight of 0.99 g) and kraft paper (weight of 1.34 g), their release time is over 480 s if we directly switch off the input voltage. However, with our electrically controlled rapid de-electroadhesion method, the release time can be reduced to 0.86 s and 0.91 s, respectively, validating the effectiveness for different substrates.

IV. CONCLUSION

In summary, this work has proposed an electrically controlled rapid de-electroadhesion method for the electroadhesive pad by applying one kind of exponential decay alternative voltage. We have analyzed the working principle of our approach and systematically investigated the influence of the parameters of the exponential decay alternative voltage on T_D. It demonstrates that exponential decay alternative voltage with a smaller decay factor, shorter lasting time, and more numbers of alternations can achieve more rapid de-electroadhesion. With the optimized parameters, the electrical de-electroadhesion approach can be used to reduce T_D by three orders, which can significantly improve the efficiency of the electroadhesive pad. Applications to various materials prove the generalization performance of this electrically controlled de-electroadhesion method. This research may pave the way for further applications of electroadhesion in the field of handling lightweight objects.

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