Toner Adhesion Force Estimation by Electric Field Activated Toner Jumping

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Toner motion is controlled by electric force, adhesion force, mechanical force, and so on, in the electrophotographic printing process. Adhesion force is an important force. Adhesion force in the absence of electrostatic force is estimated by electric field forced toner jumping. Toner is sprayed on one of a pair of electrodes that are spaced parallel to each other. Voltage increasing at a constant rate is applied to the electrode, and toner jumping starts at the voltage where electric force overcomes adhesion and gravitation forces. From the toner jumping voltage, adhesion force is estimated. Toner diameter, substrate and toner application method dependencies are obtained.

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Introduction

Electrophotographic printing is a complex process involving, in most devices, six distinct steps of charging, exposing, developing, transferring, fusing, and cleaning. In addition, each step usually interacts producing a complex phenomenon. Toner adhesion force is an important factor in developing, transferring, and cleaning processes.[1–4] Toners of 10 μm in diameter are brought into the vicinity of the latent image. Because of the electric field created by the charges on the photoreceptor, the toner adheres to the latent image and consequently transforms it into a real image. The developed toner on the photoconductor is transferred to paper by corona charging or conductive rollers at the back of the paper, with a charge opposite to that of the toner particles. The physics governing transfer is probably related to the competition between the force on toner due to the electric field caused by the charge on the paper and the adhesion force of the toner to photoconductor. This adhesion problem has been the subject of numerous investigations since 1966 with controversy about whether the adhesion is brought about primarily by image forces or van der Waals short-range forces. In the cleaning step, the photoreceptor is discharged and cleaned of any excess toner using coronas, lamps, brushes, and/or scraper blades. The physics of the cleaning process probably is related to a competition between toner adhesion to the photoreceptor and the forces on the toner caused by the cleaner. This research work aims to estimate the forces of toner jump in an increasing electric field. Preliminary measurements have been accomplished in an equipment setup that is applicable to the present studies. The force dependencies of toners and substrates will be estimated as well as the mechanism of the force.

The three objectives are as follows: to estimate the adhesion force between the toner and electrode by measuring jumping characteristics of the toner in the electric field; to measure the dependency of adhesion force on electrode materials; and to measure the dependency of adhesion force on toner particle size.

Experimental

Equipment Setup. The setup consists of the following parts: (1) power supply unit, Takasago, HV 1.5–0.5, for voltage and current adjustments; (2) electrometer, TR8651, Takeda Riken, for adjusting ampere, coulomb, ohm, and current compensatory; (3) pA meter for a dc voltage source with an ultrahigh megaohm meter, YHP 4140B, Yokogawa-Hewlett Packard; (4) sample chamber model TR-42 Takeda Riken, and (5) an X-Y chart recorder. The experimental configuration is shown in Fig. 1 (see Ref. 5).

Materials. Conductive toners of various size and various types of substrates (lower electrodes) were prepared. The toners were made conductive by the inclusion of carbon black and silica for improving flow property. Conductive toners used were G2G (14.6 μm), G2M (12.25 μm), M2G (9.43 μm), and M2M (7.7 μm). The lower electrodes used were a crystalline silicon wafer, organic photoconductor (OPC), indium tin oxide (ITO) coated glass, and stainless steel, while the upper electrode was stainless steel for most of the experiments.

Methods of Toner Application. Two methods were used for making a thin layer on the lower electrode: free falling deposit of toner powder onto the substrate or magnetic brush application with 5 or 10 V to cause toner powder to sit on the lower electrode.

Procedure. Setting of the electrical resistance appropriate to the mean particle size should be based on previous preliminary trial and error experiments. Before the toner jumping current was measured, the following data provided useful guidelines for setting up the appropriate resistance in conjunction with particle size.

Resistance, Ω-cm	10^4	10^5	10^6	10^6	10^9	10^9
Mean particle size, μm	12.4	12.1	9.20	9.9	8.85	7.25

After the appropriate resistance was set, the toner was then applied on one side of the lower parallel electrode, and two strips of insulating spacers of 500 μm (Teflon) were used to make an air gap. For some experiments, polyester strips with Teflon tape were also used to make an air gap of 600 μm. The strips were put on the lower

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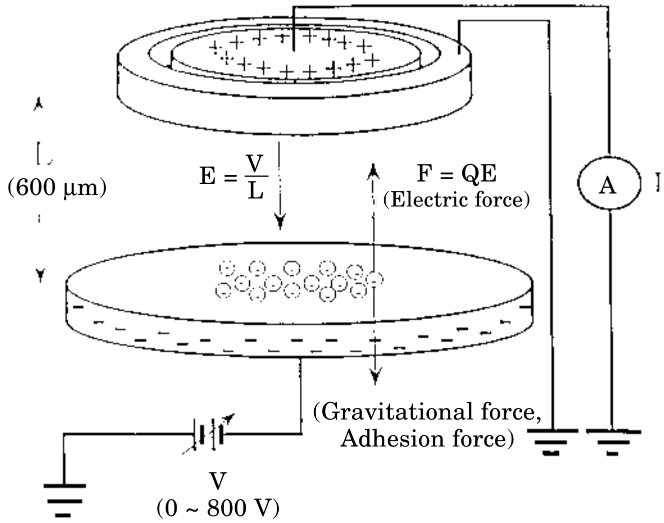

Figure 1. Experimental configuration (see Ref. 5).

electrode on the left- and right-hand sides of the toner. A guard cell or an electrode was put on the strips, and the upper electrode was put on the strips inside the guard. The upper electrode was placed at an appropriate position so that it could accept all the toner particles that jump. The circuit was then connected, experiment parameters such as V, V_A, V_B, start V_A, stop V_B, dV/dt, step V, step delay time, and chart recording speed were properly set, and the current between the two electrodes was then measured. When the electric force exceeded the adhesion force, the toner would then freely jump causing the electric current to flow. The charges induced in the toner by inductive effect and the related electric and adhesion forces were estimated. SEM photographs were taken to observe the shape and contact phenomena of the toners on the substrate as shown in Fig. 2.

Results and Discussion

According to Banerjee and Mazumder,[6] the total adhesion force is the vector sum of electrostatic, van der Waals, and gravitational forces. Force, acting between the charged particles and the conducting substrate comprise (1) the electrostatic image force of attraction between charged particles and the grounded electrode, (2) Coulombic repulsive force between toners at the electrodes, and (3) the van der Waals forces. Generally, these forces vary as functions of inductive effect and electrical resistivity, particle size, toner film thickness, and the film application technique. Hoshino and colleagues in previous experiments found that toner jump current can be written as follows[5]:

$$I = CdV/dt + I_{\text{Toner jump}}, \quad (1)$$

where

I = total current
C = capacitance of this measuring cell
= $(\varepsilon_0 S_{\text{air}} + \varepsilon_{\text{film}} S_{\text{film}})/d$
ε_0 = permitivity of the free space = 8.85×10^{-12} F/m
$\varepsilon_{\text{film}}$ = permitivity of the film
S_{air} = area where two electrodes face the air
S_{film} = area where two electrodes face the spacer film
dV/dt = rate of voltage increments, 5 V/s.

Figure 3 shows the dependence of electric current on voltage as a function of time from which the beginning voltage for toners to jump and the magnitude of electrical current due to toner jumps were obtained. When the toner at Position 1 was charged, it became active. When the electric force exceeded the adhesion force, it jumped to Position 2 as shown in Fig. 4. All charges in Fig. 4 were induced by the application of voltage. The conductive toner was noncharged initially. When the electrical force exceeds the adhesion force, the toner can jump freely. Thus the jumping would continue until the adhesion force was greater than the electric force, the toners then would stay on the electrode. At the beginning of toner jump, total force exerted on the toner shown in Eq. 2 can be deduced by Eq. 3, because at the beginning of toner jump, $F = 0$ when $V = V_{\text{th}}$.

$$F = \varepsilon_0 SE^2 - Vol\,\rho^g - f_{\text{adh}} \quad (2)$$

$$f_{\text{adh}} = \varepsilon_0 SE^2_{\text{th}} - Vol\,\rho^g \quad (3)$$

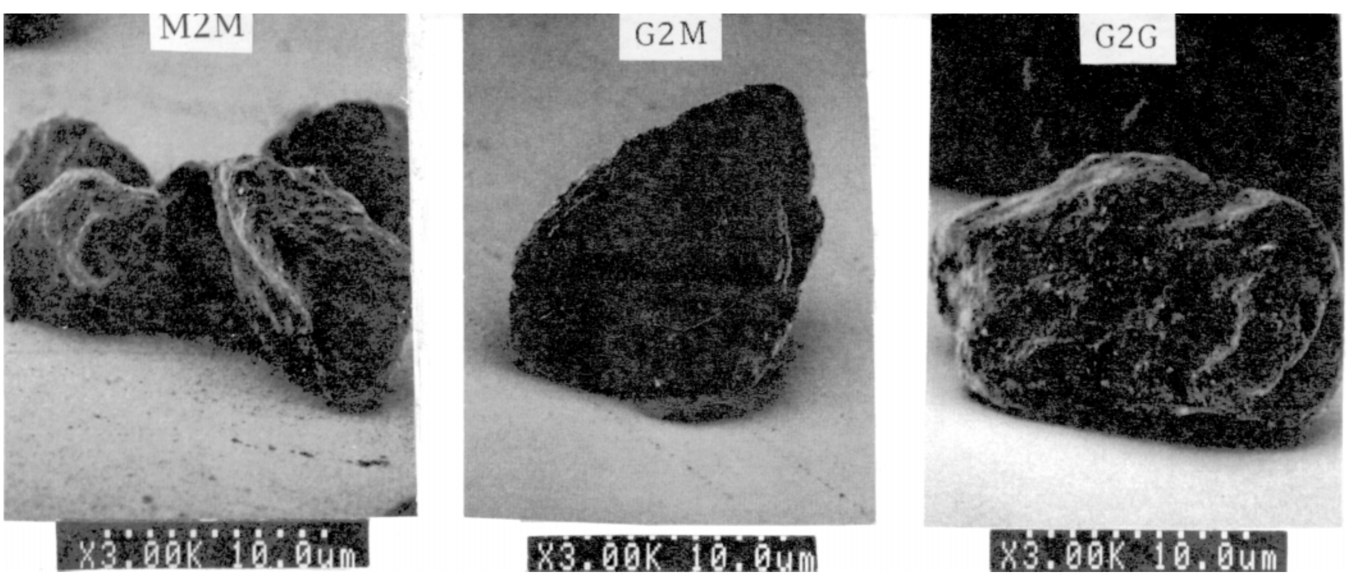

Figure 2. Scanning electron micrographs of the conductive toners with size range from medium-to-medium size (*left*), large-to-medium size (*middle*), and large-to-large size (*right*).

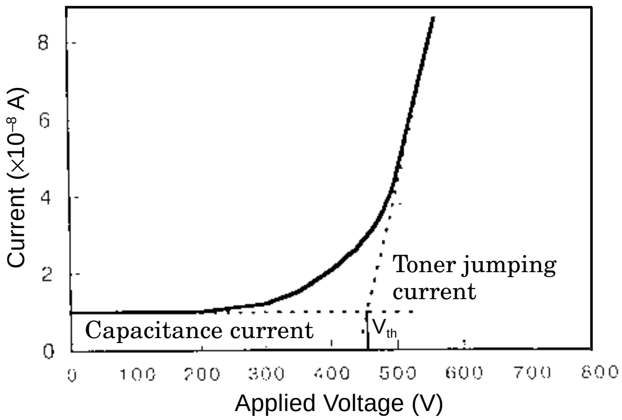

Figure 3. Dependency of current on voltage for toner jump. (V_{th} = the voltage at which a toner begins to jump.)

where

E_{th} = electric field when V_{th} is applied
ε_0 = permitivity of the free space 8.85×10^{-12} F/m
S = effective cross section of toner particle (m^2)
Vol = toner volume (m^3)
ρ = specific gravity of toner (kg/m^3)
g = acceleration of gravity (m/s^2)
f_{adh} = adhesion force of toner (N).

Because $V\rho^g$ is negligible comparing to the magnitude of $\varepsilon_0 S E_{th}^2$, the former can be eliminated. In addition, the values of E_{th} can be obtained from Eq. 4, because the space between electrodes is 0.6×10^{-3} m:

$$E_{th} = V_{th}/0.6 \times 10^{-3}. \tag{4}$$

For S, one can make use of volume-average particle size from a Coulter Counter experiment as follows:

$$\begin{aligned} S &= \alpha \pi^{1/3}(3\ V/4)^{2/3} \\ &= 4\ \pi^{1/3}(3\ V/4)^{2/3} \end{aligned} \tag{5}$$

where α is the coefficient of the effective cross-sectional area of the toner particle. The shape of the toner can be considered almost spherical from Fig. 2. Therefore, the coefficient α is set as $\alpha = 4$ based on electromagnetic theory. In this case, one can assume that the electric force lines focus onto the conductive spherical toner in a uniform electric field.

To calculate the adhesion force of toner jump f_{adh}, the following equation can be used:

$$f_{adh} = \varepsilon_0 S E_{th}^2, \tag{6}$$

$$f_{adh} = 8.85 \times 10^{-12} \times 4\pi^{1/3}(3\ V/4)^{2/3}[V_{th}/0.6 \times 10^{-3}]^2. \tag{7}$$

Table I summarizes the data and gives the calculated E_{th}.

Dependence of V_{th} and E_{th} on Electrodes. Tables II and III show the calculated results of E_{th} and f_{adh} of the experiments. The types of electrodes such as stainless steel and conductive glass show significantly different jumping voltages of the toners as shown below:

Stainless steel	V_{th} (V)	543	403	330	272
Conductive glass	V_{th} (V)	473	337	313	238

The results of V_{th} and E_{th} in Table II indicated that the values of V_{th} and E_{th} are in inverse relationship with the size of the toner. This was found both for the stainless steel and the conductive glass electrodes. With the same toner size, both values of the conductive glass are lower than those of the stainless steel. It is thought that these electrode materials have sufficient conductivity, and the difference is because of different surface structure.

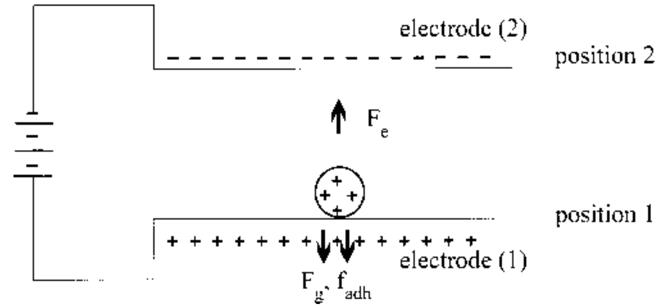

Figure 4. Position of toner jumping between electrodes.

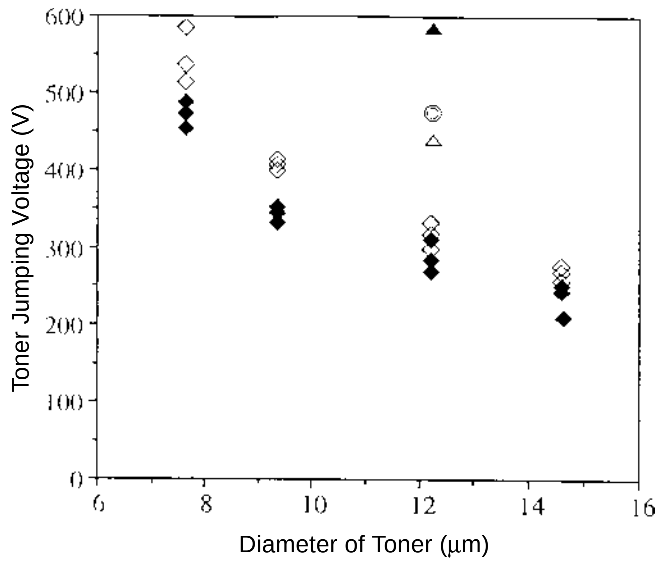

Figure 5. Dependency of toner jumping voltage on application methods and toner particle sizes.
Distance between two electrodes: 600μm. Electrodes: Conductive silicone wafer. Indium tin oxide, (ITO)
Voltage increasing rate: 5 V/s
◇ Free falling, on the stainless steel
◆ Free falling, on the ITO glass
◎ Wipe-on using Kim-wipe on the silicone wafer
△ Magnetic brush, 5 V, the silicone wafer
▲ Magnetic brush, 10 V, the silicone wafer

The f_{adh} values calculated from Eq. 7 depend on the toner size and the values of V_{th}; the latter is inversely proportional to the toner size roughly. In addition, f_{adh} is directly proportional to the conductivity of the electrodes (see Table III). We found that the order of f_{adh} is as follows:

silicon (amorphous)< conductive glass
< silicon (crystalline) < stainless steel

	stainless steel	conductive glass	silicon crystalline	silicon amorphous
V_{th} (V)	330	313	328	287
f_{adh} ($\times 10^{-10}$ N)	12.6	11.4	12.5	9.6

The amorphous silicon film was illuminated with light to make it conductive. Without the light illumination, the

TABLE I. Toner Jumping Voltage V_{th} and Toner Jumping Electric field E_{th}, of Several Types of Toners.

Name of toner	D*	Application method	Types of electrodes: Stainless steel	Silicon crystalline	Silicon amorphous	Conductive glass
M2M	7.70	Free falling	$543 \pm 3.329 \times 10$ $E_{th} = 9.1 \times 10^5$	—	—	$473 \pm 1.5275 \times 10$ $E_{th} = 7.89 \times 10^5$
M2G	9.43	Free falling	$403 \pm 1.0408 \times 10$ $E_{th} = 6.7 \times 10^5$	—	—	337 ± 5.7735 $E_{th} = 5.6 \times 10^5$
G2G	14.60	Free falling	272 ± 2.8868 $E_{th} = 4.5 \times 10^5$	—	—	$238 \pm 2.8868 \times 10$ $E_{th} = 4.0 \times 10^5$
G2M	12.25	Free falling	330 ± 5.0000 $E_{th} = 5.5 \times 10^5$	$328 \pm 2.0817 \times 10$ $E_{th} = 5.5 \times 10^5$	—	313 ± 7.6376 $E_{th} = 5.2 \times 10^5$
		Free falling + light	—	—	$287 \pm 2.2546 \times 10$ $E_{th} = 4.8 \times 10^5$	—
		Magnetic brushing	55 ± 0.0000 $E_{th} = 9.2 \times 10^5$	$488 \pm 7.9425 \times 10$ $E_{th} = 8.1 \times 10^5$	—	—
		Kim-wiper rubbing	—	475 ± 0.0000 $E_{th} = 7.9 \times 10^5$	—	—
BC†		Free falling	—	—	$254 \pm 1.2583 \times 10$ $E_{th} = 4.2 \times 10^5$	—

* Volume-averaged diameter

† BC: Toner before classification

TABLE II. V_{th}, E_{th}, and f_{adh} of Various Toners by Free Falling Application on Electrodes.

Name of toner	D*μm	Stainless steel V_{th}	$E_{th} \times 10^{-3}$	$f_{adh} \times 10^{10}$	Conductive glass V_{th}	$E_{th} \times 10^{-3}$	$f_{adh} \times 10^{10}$	Silicon film, Crystalline V_{th}	$E_{th} \times 10^{-3}$	$f_{adh} \times 10^{10}$	Silicon film, Amorphous‡ V_{th}	$E_{th} \times 10^{-3}$	$f_{adh} \times 10^{10}$
M2M	7.7	543	905	13.5	473	788.3	10.3	—	—	—	—	—	—
M2G	9.43	403	672	11.2	337	561.7	7.8	—	—	—	—	—	—
G2M	12.25	303	550.0	12.6	313	521.7	11.4	328	546.7	12.5	287	487.3	9.6
G2G	14.60	272	453.3	12.2	238	396.7	9.3	—	—	—	—	—	—
BC	—	—	—	—	254	423.3	—	—	—	—	—	—	—

* The amorphous silicon film was illuminated with light

TABLE III. V_{th}, E_{th}, and f_{adh} of G2M Toners by Various Application Methods.

Application methods of toner	Stainless steel V_{th}	$E_{th} \times 10^{-3}$	$f_{adh} \times 10^{10}$	Conduvtive glass V_{th}	$E_{th} \times 10^{-3}$	$f_{adh} \times 10^{10}$	Silicon, Crystalline V_{th}	$E_{th} \times 10^{-3}$	$f_{adh} \times 10^{10}$	Silicon, Amorphous* V_{th}	$E_{th} \times 10^{-3}$	$f_{adh} \times 10^{10}$
Free falling	330	550	12.6	313	521.7	11.4	328	546.7	12.5	287	478	9.6
Magnetic brush	55	91.7	0.35	—	—	—	488	813.3	27.6	—	—	—
Kim-wipe rubbing	—	—	—	—	—	—	475	791.7	26.2	—	—	—

* The amorphous silicon film was illuminated with light

amorphous silicon film was inactive to voltage activation and the toner could not jump at all. In conclusion, when the substrate is resistive, toner charging cannot be induced.

Dependence of V_{th} and E_{th} on Toner Application Methods. It is thought that adhesion force is dependent on the method of toner application to the electrode, because the force is mainly determined by the microscopic distance between toner and electrode.[7] In Table II, when the electrode is the silicon crystalline type, the following result can be obtained.

	V_{th}(V)	f_{adh} ($\times 10^{-10}$ N)
Free falling	328	12.5
Kim-wipe rubbing	475	26.2
Magnetic brushing	488	27.6

The results suggest that application of additional force above and beyond the gravitational force makes the distance between the toner and electrode shorter. Then the toner jumping voltage and the adhesion force can be enhanced. The values obtained in these experiments are somewhat smaller, compared to the data of Refs. 1 and 2, which may be caused by the absence of electrostatic force.

Dependence of toner jumping voltages on toner application methods and toner particle sizes. Figure 5 shows the dependence of toner jumping voltages on toner application methods and toner diameters. The smaller the toner size, the higher the toner jumping voltage. The small toner has less mass and its weight is therefore lighter, but the electric force on toner becomes smaller as toner diameter becomes smaller. Under coating with application of electric force, i.e., magnetic brush application, the adhesion force becomes greater as shown Fig. 5. Perhaps when force is applied to attach the toner onto the lower electrode, the distance between the toner and the electrode becomes smaller; the contact areas are thus larger. For toner sizes ranging from 8 to 15 μm, an adhesion force of 0.5×10^{-9} N could be obtained.

Conclusion

Toner jumping was detected by measuring the current between electrodes, at certain electric fields, to provide information about toner adhesion force. The adhesion force dependencies on toner size, substrate materials, and toner application method were accordingly obtained.

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References

1. C. J. Mastrangelo, The effect of charge, size, and shape on toner photoconductor adhesion in electrophotographic systems, *Photo. Sci. and Eng.* **26 (4):** 194–197 (1982).
2. M. H. Lee and J. Ayala, Adhesion of toner to photoconductor, *J. Imag. Tech.* **11 (8):** 279–284 (1985).
3. D. A. Hays, Adhesion of charged particles, *J. Adhesion Sci. Technol.* **9 (8):** 1063–1093 (1995).
4. E. A. Eklund, W. H. Wayman, L. J. Brillson and D. A. Hays, Toner adhesion physics, Proceedings of IS&T's 10th International Congress on Non-Impact Printing, 142–146 (1994).
5. Y. Hoshino, S. Kiatkamjornwong, S. Noppakundilograt, and Y. Ando, Adhesion force estimation from toner jumping by electric field: Difference in adhesion methods, *Extended Abstracts of the 55th Autumn Meeting of the Japan Society of Applied Physics*, 1994.
6. S. Banerjee and M. K. Mazumder, Adhesion of charged powders on metal surface in powder coating process, IEEE IAS 28th Annual Meeting Proceedings, **2:** 1897–1901 (1993).
7. H. Krupp and G. Sperling, Theory of adhesion of small particles, *J. Appl. Phys.* **37 (11):** 4176–4180 (1966).