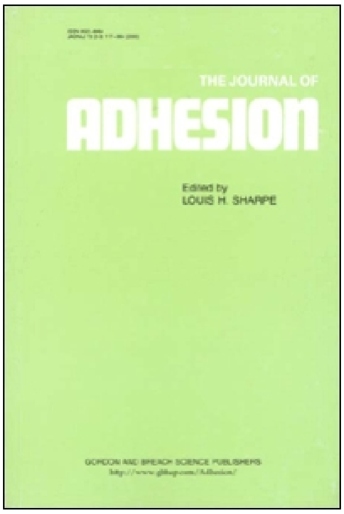

The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

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Dan A. Hays[a]
[a] Wilson Center for Research and Technology, Xerox Corporation, Webster, NY, U.S.A.

To cite this Article Hays, Dan A.(1995) 'Toner Adhesion', The Journal of Adhesion, 51: 1, 41 — 48
To link to this Article: DOI: 10.1080/00218469508009988
URL: http://dx.doi.org/10.1080/00218469508009988

J. Adhesion, 1995, Vol. 51, pp. 41–48
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Toner Adhesion*

DAN A. HAYS

Wilson Center for Research and Technology, Xerox Corporation, 0114-22D, 800 Phillips Rd., Webster, NY 14580 U.S.A.

(Received September 5, 1994; in final form December 17, 1994)

The adhesion of toner particles charged by triboelectricity plays an important role in the electrophotographic process. In spite of the importance of this phenomenon to electrophotography, the physics of toner adhesion is not well understood. A literature survey of toner adhesion measurements reveals adhesion forces which are typically 5 to 50 times larger than the predictions of the electrostatic image force model, a description which treats the irregularly-shaped toner particles as spheres with uniform charge density. To account for this discrepancy and other observed behavior, a toner adhesion model is presented which assumes a highly non-uniform surface charge distribution. This charge patch model explains the results of electric field detachment studies, which show enhanced adhesion and the absence of strong selectivity in toner charge and size.

KEY WORDS electrophotography; toner; adhesion; charged particles; charge patch model; non-uniform surface charge distribution; triboelectricity.

INTRODUCTION

The use of electric fields to controllably move charged, pigmented particles, called toner, is central to the electrophotographic process. A uniformly-charged photoconductor is exposed to an imagewise source of light, creating an electrostatic latent image which can be developed with toner. This developed image is then transferred and fused to paper by first applying a charge (opposite polarity to the toner) to the back of the paper, followed by heat and pressure. A cleaning step, to remove residual toner from the photoconductor, completes the process.[1]

For electrophotographic copiers, imagewise light exposure is obtained by using a lens to focus the illuminated original document onto the charged photoconductor. In the case of electrophotographic printers, the imagewise exposure is usually obtained with either a scanning, modulated laser beam or a LED array. The toner particles used in the electrophotographic process are $\sim 10\,\mu m$ in diameter and are charged by the phenomenon of triboelectricity. The toner is supplied to a development system which usually contains larger particles called carrier beads. The mixing of toner with the carrier beads causes the toner to acquire a triboelectric charge of the desired polarity and magnitude, enabling its transfer *via* an electric field. During the development step, the electric field from the electrostatic image attracts toner particles from the carrier

* Presented at the Seventeenth Annual Meeting of The Adhesion Society, Inc., in Orlando, Florida, U.S.A., February 21–23, 1994.

beads to the photoconductor. In the development and transfer steps, the movement of charged toner from one surface to another by an electric field requires an electrostatic force to overcome the force of adhesion between the charged particle and the original substrate. If the adhesion is too high, the toner transfer efficiency will be low, resulting in poor image quality. Clearly, the adhesion properties of toner particles are of considerable importance in the functioning and optimization of the electrophotographic process.[1,2]

The toner used in most of the current electrophotographic machines is irregular in shape, since the particles are formed by a grinding process. Many adhesion studies on irregularly-shaped toner particles have been reported over the past 30 years.[3-11] It is the purpose of this paper to review the recent data on toner adhesion, obtained by centrifuge and electric field detachment methods, and to compare these measurements with the predictions of toner adhesion models.

IMAGE FORCE MODEL

Assuming that an irregularly-shaped toner particle can be approximated as a dielectric sphere with the charge uniformly distributed over the surface, the electrostatic image force on the particle from a planar, conductive substrate can be calculated as

$$F_I = -\alpha \frac{Q^2}{4\pi\varepsilon_0 D^2} \tag{1}$$

where Q is the particle charge, D is the average diameter, ε_0 is the permittivity of free space and α is a correction factor which depends on the polarization of the dielectric particle. (For a dielectric constant of $\kappa = 4$, $\alpha = 1.9$.)[7] For a typical toner particle with a charge-to-mass ratio of $15\,\mu C/g$ and an average toner diameter of $10\,\mu m$, the particle charge, Q, is 8 fC. The magnitude of the electrostatic image force calculated from Equation (1) is ~ 10 nN.

When an external electric field is applied to a uniformly-charged dielectric sphere, the electrostatic detachment force is

$$F_E = \beta Q E - \gamma \pi \varepsilon_0 D^2 E^2 \tag{2}$$

where E is the applied electric field and β and γ are polarization correction factors (1.6 and 0.063, respectively, for $\kappa = 4$). Electric field detachment occurs when $F_I + F_E \geqslant 0$. (Contributions from short-range and/or contact forces are neglected here.) Since the second term in Equation (2) can be neglected for relatively low fields, the detachment electric field is

$$E_D \simeq \frac{\alpha Q}{\beta 4\pi\varepsilon_0 D^2}. \tag{3}$$

For the above set of typical values, E_D is ~ 1 V/μm.

LITERATURE REVIEW

Table I summarizes measurements reported in the literature of toner adhesion forces obtained by the centrifuge method. Representative values for the measured and calculated adhesion forces (according to Eq. (1)) are also displayed in Figure 1a as a function of the average toner charge-to-diameter ratio. The typical measured toner adhesion is 5 to 50 times larger than the calculated value. An attempt to address this large discrepancy can be made by including short-range and/or contact forces in the calculated adhesion. (One can show from model calculations that the short-range and/or contact forces between a dielectric sphere and planar substrate can be comparable with the measured values.) However, if such short-range forces are dominant, it follows that the adhesion should be independent of toner charge, which is contrary to the measurements shown in Table I and displayed in Figure 1a.

A survey of the literature on electric field detachment reveals a similar discrepancy between measured and calculated toner detachment fields. The data in Table II and Figure 1b show that the measurements for the average detachment electric field range from 5 to 15 V/μm, more than an order of magnitude higher than the calculations obtained from Equation (3).

In addition, when toner is incrementally detached from a substrate with an increasing electric field, one would expect the charge and size of the detached toner particles to vary with the applied field according to Equation (3). This charge and size selectivity is not observed in experiments; rather, the charge and size of the detached toner is essentially independent of the applied electric field.[7,9]

It is clear from these comparisons that a simple electrostatic image force model fails to describe the adhesion behavior of triboelectrically-charged toner particles. Clearly, an alternative toner adhesion model is required which accounts for the irregular shape and the expected non-uniform distribution of charge on the surface of real toner particles.

TONER CHARGE PATCH MODEL

Figure 2 illustrates an irregularly-shaped toner particle which has been triboelectrically charged by mixing with larger carrier beads. This commonly-used method of

TABLE I
Centrifuge measurements

Ref.	Size (μm)	Q/M (μC/g)	Q/D (fC/μm)	Adhesion (nN), Meas.	Adhesion (nN), Calc.	Ratio, Meas./Calc.
8	20	5	1	800	17	47
8	20	10	2	2000	68	29
8	20	30	6	4000	610	7
10	10	~0	~0	50	~0	–
10	10	12	0.62	300	6.6	45
11	10	5	0.26	43	1.2	36
11	10	8	0.52	55	4.6	12
11	10	16	0.84	140	12	12

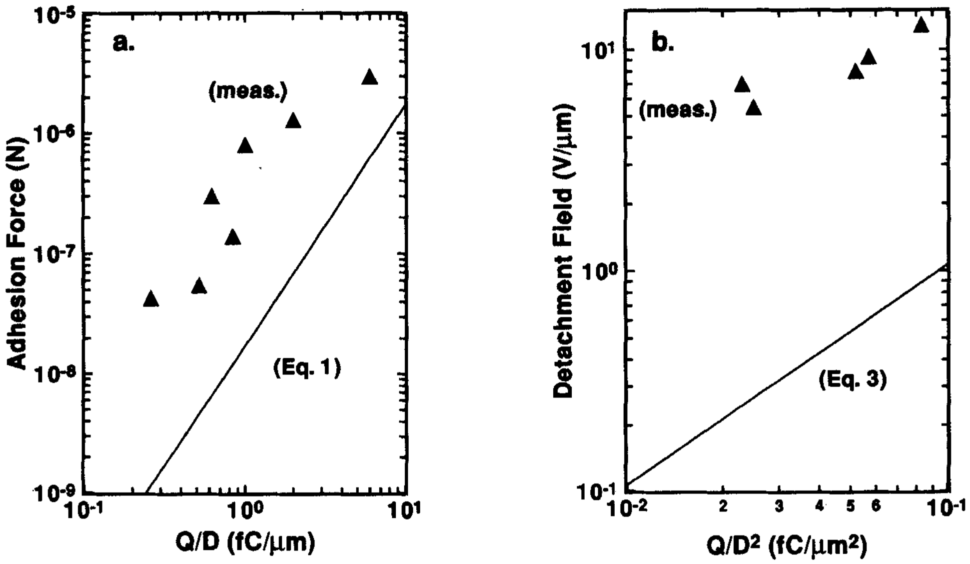

FIGURE 1 a) Comparison of the average toner adhesion forces obtained by centrifuge measurements with electrostatic image force model calculations as a function of the average toner charge-to-diameter ratio. b) Comparison of measured average detachment electric fields with electrostatic image force model calculations as a function of the ratio between the average toner charge and square of the average particle diameter.

TABLE II
Electric field detachment measurements

Ref.	Size (μm)	Q/M (μC/g)	Q/D^2 (fC/μm²)	Field (V/μm), Meas.	Field (V/μm), Calc.	Ratio, Meas./Calc.
3	12	4	0.025	5.5	0.26	21
3	12	9	0.058	9.3	0.61	15
3	12	13	0.083	13	0.88	15
7	21	5	0.052	8	0.58	14
9	9	5	0.023	7	0.25	28

toner charging is expected to lead to a highly non-uniform surface charge distribution. In order to account for this non-uniform charging, a charge patch model of toner adhesion has been proposed.[7,8] This model assumes that the protrusions on the insulative particle are charged to an essentially constant surface charge density, σ, that depends on the triboelectric charging properties of the toner and carrier bead materials. The total charged area, A_t, on the particle represents a small fraction of the toner surface area. Thus, the particle has a total charge $Q = \sigma A_t$. The sum of the charged areas in close proximity to the conducting substrate is A_c. If the extent of a charged area in contact with the substrate is much larger than the average distance between the charged surface and a conductive substrate, the magnitude of the electrostatic force of

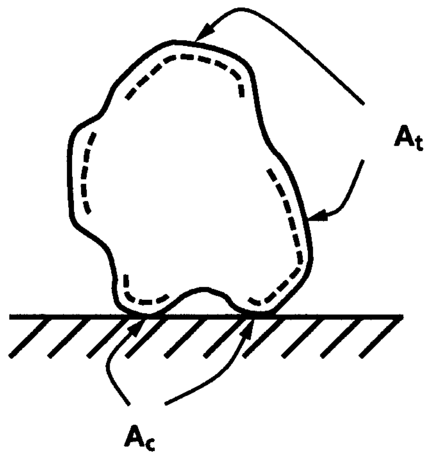

FIGURE 2 An irregularly-shaped toner particle with triboelectrically charged patches of charge density, σ. The total charged area is A_t and the sum of the charged areas in contact with the substrate is A_c.

adhesion can be expressed as

$$F_E = \frac{\sigma^2 A_c}{2\varepsilon_0}. \tag{4}$$

The total toner adhesion can be written as

$$F_A = \frac{\sigma^2 A_c}{2\varepsilon_0} + WA_c = Qf\left[\frac{\sigma}{2\varepsilon_0} + \frac{W}{\sigma}\right] \tag{5}$$

where $Q = \sigma A_t$ and the area ratio $f \equiv A_c/A_t$. A non-electrostatic adhesion contribution of WA_c has also been included. It is assumed that the appropriate contact area for the non-electrostatic component can be much less than A_c. Our assumption here is that this contact area is proportional to the area, A_c, that is appropriate for the charged areas on the toner particle in close proximity to the substrate. The proportionality factor W depends on the microscopic surface roughness and material properties.

To estimate the electrostatic component of adhesion, we assume that the average value of f is 0.2; that is, the average of the charged areas in close proximity to the substrate is approximately one-fifth of the total charged area. From a survey of the literature on contact charging, σ can range from 0.5 to 5 mC/m^2 for different combinations of triboelectrically-active materials.[12] For $\sigma = 1$ mC/m^2 and $Q = 8$ fC, the electrostatic contribution to the adhesion force is ~ 100 nN, which is comparable with the measured values listed in Table I.

When an electric field is applied to toner, the electrostatic force of detachment is QE. (For irregularly-shaped particles, we neglect the polarization correction terms as given by Equation (2) for spherical particles.) By equating QE to the expression in

Equation (5), the detachment electric field, E_D, is given by

$$E_D = f\left[\frac{\sigma}{2\varepsilon_0} + \frac{W}{\sigma}\right]. \tag{6}$$

For $f = 0.2$ and $\sigma = 1\ \mathrm{mC/m^2}$, the electrostatic component of the detachment electric field is $\sim 10\ \mathrm{V/\mu m}$, which is comparable with the measured values listed in Table II.

DISCUSSION

In addition to these specific examples, the behavior predicted by the charge patch model is consistent with a wide body of experimental observations. For instance, if one assumes that the area ratio, f, is not a strong function of the toner particle size, Equation (6) predicts that electric field transfer of toner is essentially independent of particle size and charge. This implies that in the incremental detachment of toner by an electric field, the charge-to-mass ratio of the detached toner is independent of the detachment electric field. This behavior is observed experimentally.[7,9] Furthermore, the distribution in the electric fields required to detach toner from a substrate is attributed to a distribution in the values of f and, therefore, a distribution in contact areas. This implies that the electrostatic adhesion of a given toner particle is not unique, but can vary widely according to the area of charge in close proximity to the substrate. This prediction has been confirmed with an experiment in which toner, transferred from one electrode to another by a relatively low electric field, requires a much higher electric field for transfer back to the original electrode.[7]

In addition, according to Equation (5), the distribution in the adhesion of toner is controlled by the product of the distributions in toner charge and in the area ratio, f. Distributions in toner charge can span up to two orders of magnitude.[9] The width of the distribution in f can be obtained by measuring the incremental toner transfer as a function of the electric field when transferring toner from a donor to a receiver electrode. Figure 3 shows the fractional toner mass transferred per unit electric field as a function of the applied electric field.[7] The distribution in the applied electric field, and hence the distribution in f, is about one order of magnitude. For comparison, centrifuge measurements of toner adhesion exhibit a wide range of forces which span several orders of magnitude.[11] This wide distribution in the measured toner adhesion is therefore, consistent with the product in the distributions for the toner charge and the area ratio, f.

Finally, according to Equation (4), it is expected from the charge patch model that the adhesion force should vary quadratically with Q/D. This dependence follows from Equation (4) which can be rewritten as

$$F_E = \frac{Q^2 f}{2\varepsilon_0 A_t} \tag{7}$$

It is assumed that A_t is proportional to D^2, and f is not a strong function of D. As can be seen in Figure 1a, the adhesion data obtained by centrifuge measurements is roughly

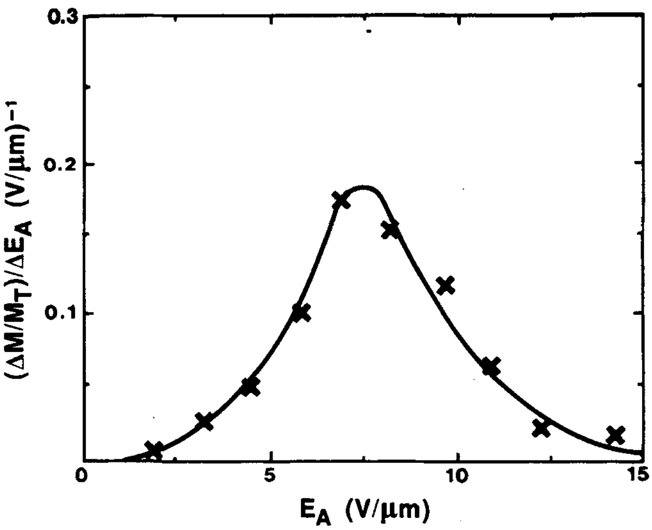

FIGURE 3 Fractional toner mass transferred per unit electric field as a function of the applied electric field for 21 μm toner loaded on a donor electrode with a coverage of 0.85 mg/cm^2.

consistent with a quadratic dependence on Q/D. This power law dependence was also reported by Donald.[5] While the electrostatic image force model of Equation (1) also predicts the same quadratic dependence, the magnitude is too low by a factor of ~ 40.

It is important to emphasize that the charge patch model for toner adhesion assumes that the protrusions on an insulative particle are triboelectrically charged to a high charge density. Since the electric field near a localized charge patch can be quite high, one might expect charge spreading if the surface is sufficiently conducting, especially under high relative humidity conditions. Although some charge spreading cannot be ruled out, significant charge redistribution on the surface is not anticipated, since it is well known that the charge of toner resting on carrier beads is remarkably stable over a period on the order of weeks. This toner charge stability implies that a low surface conductivity prevents significant charge spreading and migration across the toner-carrier bead interface.

SUMMARY

The large discrepancy between predictions of the image force model and measurements of toner adhesion is the impetus for a more realistic model of toner adhesion. This new description, the charge patch model, assumes a highly non-uniform surface charge distribution on irregularly-shaped toner which is charged by triboelectricity. It is highly successful in explaining the high adhesion observed in experiments and its dependence on toner charge. Furthermore, the model accounts for the observation that essentially no selectivity in toner charge or size is obtained, in spite of broad charge and size distributions seen for typical toner materials. This toner adhesion characteristic is a

consequence of non-uniform surface charging and has important benefits for the long-term stability of xerographic development systems. If strong selectivity in toner charge and size were to occur as toner flows through the development system, the xerographic performance of the developer would rapidly degrade.

Acknowledgements

The author would like to thank Drs. Elliott Eklund, Howard Mizes and Mary Ott for their critical reading of the manuscript and stimulating discussions.

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