Toner Adhesion Physics: Measurements of Toner/Substrate Contact Area

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Abstract

We have studied electrostatic detachment of charged toner particles with a specially developed transfer cell which allows direct measurements of the toner surface area in contact with a substrate as a function of the applied field. We have used these measurements to test the predictions of the charge patch model of toner adhesion. This model assumes a non-uniform distribution of charge on the toner particles, which significantly enhances the electrostatic component of adhesion, and predicts that the overriding factor governing toner adhesion is the particle surface area closest to the substrate. Our results provide significant new evidence in support of the charge patch model and lead to a better understanding of the adhesion forces which govern toner transfer in electrophotographic development.

Introduction

Despite the fact that the transfer of toner between surfaces is a requirement for several process steps in electrophotography,[1] the fundamental physics governing toner adhesion is poorly understood. The ability to predict and control the behavior of xerographic toner depends on a proper description of adhesion forces, particularly as toner size is decreased to enable high resolution color prints. The simplest model of toner adhesion relies solely on electrostatic forces, and assumes that the toner particles can be approximated by spheres with uniform surface charge density. In this case, the magnitude of the electrostatic image force which provides the adhesion between the toner particle and a conducting surface is given by,

$$F_I = \alpha q^2/4\pi\varepsilon_0 d^2 \qquad (1)$$

where q is the particle charge, d is the average particle diameter and ε_0 is the permittivity of free space. For a dielectric constant of 4, the polarization correction, $\alpha = 1.9$. Typically q = 8 fC and d = 10-20 μm, which give an image force from Eqn. (1) of approximately 10 nN, while the results from centrifuge experiments are 10 to 300 times larger.[2-5] This discrepancy has led to models in which short range and/or contact forces provide the bulk of the adhesion.[6] If this is true, however, the adhesion should be independent of toner charge, contrary to results from centrifuge and electrostatic detachment studies.[2-5,7-11]

Figure 1 is an electron micrograph of toner particles developed onto a conducting electrode at a coverage of approximately 0.5 mg/cm². Note that the particles are highly irregular and non-spherical in shape due to the grinding process used in toner manufacture. Toner is charged triboelectrically by mixing with larger carrier beads, a process which is expected to produce charge primarily on the areas of most intimate contact. Considering these departures of real toner particles from perfect spheres, and the disagreement discussed above between forces calculated with Eqn. (1) and experimental measurements, a more realistic model of toner adhesion is needed, a model which includes the effects of irregular particle shapes on the distribution of charge and toner/substrate contact geometry.

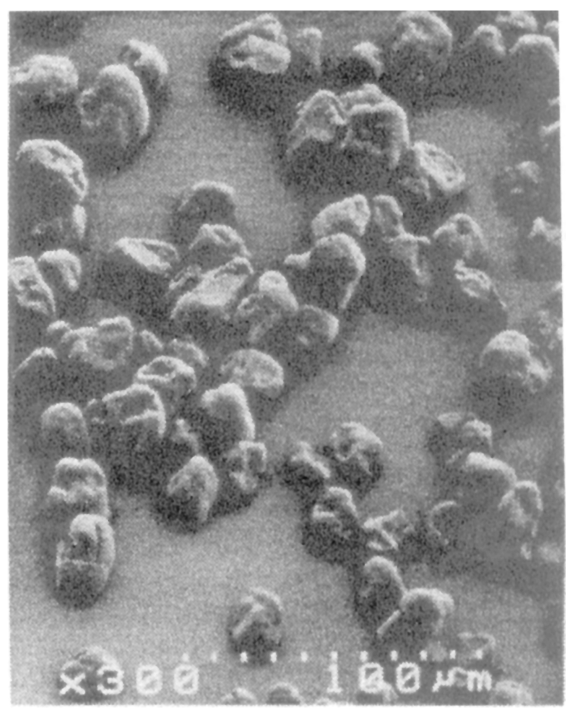

Figure 1. Toner particles of 20 μm average diameter deposited at a coverage of 0.5 mg/cm².

A description of adhesion which satisfies these requirements is the charge patch model.[3,7,8] Figure 2 depicts a charged, irregularly shaped toner particle. Triboelectric charging produces a charge density σ on the protruding regions of the particle. It is assumed that, for a particular set of toner and carrier bead materials mixed at a certain toner concentration, the charge density σ is nearly constant. A_t is the total charged area on the particle and the sum of the charged areas in contact with the substrate is denoted by A_c. The model also assumes that the extent of a charged area in contact is much greater than the average distance between the charged surface and the substrate. For these conditions the electrostatic component of adhesion can be approximated by the expression for the force between two oppositely charged sheets. In addition, the model assumes the presence of nonelectrostatic forces, which also depend on the area of contact between the particle and the substrate. The total adhesion force is

$$F_a = \sigma^2 A_c/2\varepsilon_0 + WA_c = qf[\sigma/2\varepsilon_0 + W/\sigma] \quad (2)$$

where WA_c is the non-electrostatic component of adhesion, $q = \sigma A_t$ is the total charge on a toner particle, and $f = A_C/A_t$ is the ratio of the contact area to the total charged area on the particle. It is assumed that the force of adhesion due to the remaining charge on the particle, which is given by Eqn. (1), can be neglected in comparison to the force given by Eqn. (2). Also, since the electrostatic force has a longer range than the nonelectrostatic force, the actual contact areas for the two will differ. The model assumes that the area associated with the non-electrostatic force is proportional to the area of the charge patches, A_c. For $q = 8$ fC, $\sigma = 100$ nC/cm^2 and $f = 0.2$ (estimated from particle morphology), the electrostatic component of the total force of adhesion is 100 nN, an order of magnitude larger than the result of Eqn. (1) and comparable to experimentally measured values.

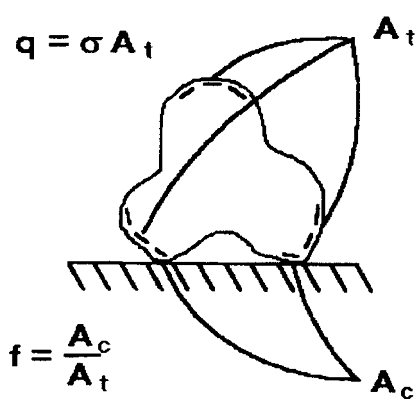

Figure 2. An irregularly shaped, charged toner particle.

For a spherical charged particle, the applied force due to an external electric field E is given by[7,8]

$$F_E = \beta qE - \gamma\pi\varepsilon_0 E^2 \quad (3)$$

where ß and γ are correction factors due to the polarization of the particle by the applied field. For the irregular particles we have used, however, we neglect polarization force contributions and set ß = 1 and $\gamma = 0$. Therefore, the field at which the particle is detached is given by

$$E_D = f[\sigma/2\varepsilon_0 + W/\sigma] \quad (4)$$

Electrostatic detachment studies thus provide a direct means for probing the distribution of toner contact areas with a substrate, thereby testing the predictions of the model expressed in Eqn. (2).

Experimental

Electrostatic detachment of toner particles has been used previously to investigate toner adhesion.[7] In this study, we have made improvements to this technique to enable direct measurements of the average contact area. Figure 3 is a schematic diagram of the apparatus used to measure the contact area of charged toner particles adhered to a conducting electrode. The transfer cell consists of two transparent, conducting electrodes, each possessing a sensor to detect the presence of toner.[12] The electrodes are held apart by an insulating spacer. The detection system operates on the principle of frustrated total internal reflection. A prism mounted to the back of each electrode allows an infrared light beam ($\lambda = 940$ nm) to enter and reflect from the front face of the plate. The light undergoes total internal reflection, creating an evanescent electromagnetic field just outside the surface of each electrode. (In the gap, the evanescent field falls off exponentially with distance from the electrode surface; the l/e length is ~ 0.2 µm.) Toner particles deposited on this surface allow some of the light to be transmitted into the gap, thus reducing the reflected intensity in proportion to the toner contact area. By monitoring the intensity of the totally internally reflected beam, it is possible to obtain a direct measure of the average contact area of the toner particles on each electrode as they are transferred across the gap by the applied electric field.

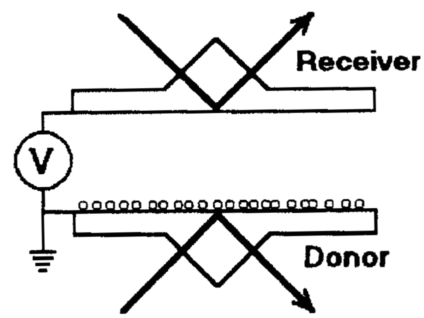

Figure 3. Schematic diagram of the transfer cell used to measure toner-substrate contact area as a function of applied voltage V

Toner is initially deposited on the donor electrode by means of a development system in which a toner cloud is formed by an AC voltage applied to a toned roll assembly. The toner coverage is varied by changing the speed of the donor electrode as it passes over the development system, holding all other electrical deposition conditions constant. For the data presented here, the volume average particle diameter is 20 µm and the average q/d ratio (from charge spectrograph measurements[13] of the transferred particles) is -1 fC/µm. Thus q, the charge per particle, is approximately -20 fC. The toner coverage was kept below one monolayer (1.2 mg/cm^2) to avoid significant stacking of particles. (Second layer particles are not detected by the evanescent wave sensors.) The gap between the electrodes is 250 µm and the maximum field possible is 18 V/µm. To avoid air breakdown at fields above 7V/µm, the transfer cell was placed in a vacuum chamber and evacuated to pressures below 10^{-5} Torr before applying any voltage. The electric field ramp and the acquisition of signals from the sensors are both computer controlled, allowing simultaneous measurements of the toner contact areas on both electrodes as a function of the electric field between them.

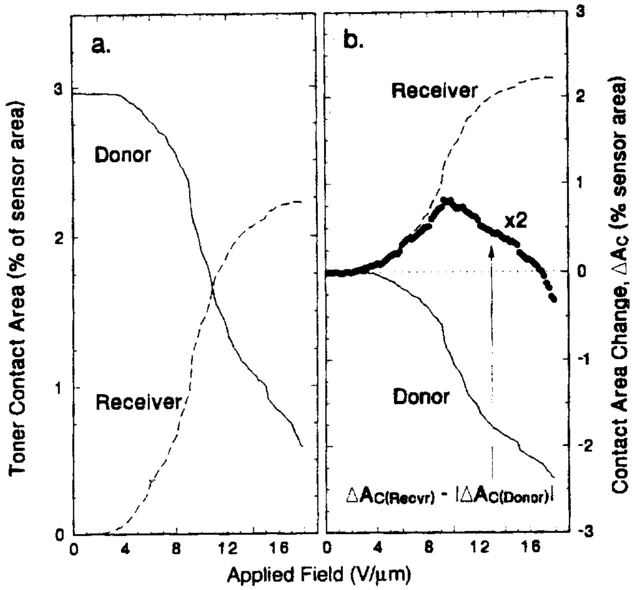

Figure 4. Changes in toner contact area on the transfer cell electrodes as a function of the applied field. In panel b, the filled circles show the difference in contact area change between the receiver and donor. The initial toner coverage on the donor electrode is 0.32 mg/cm².

Figure 4a shows plots of the toner contact areas on both electrodes as a function of the applied electric field for an initial coverage on the donor plate of 0.32 mg/ cm^2 (~ 1/4 monolayer). To allow a comparison of the data from the donor and receiver electrodes on the same scale, the results for A_C are plotted as a percentage of the total sensor area on the electrode. (The two electrodes have slight differences in sensitivity and sensing area.) As expected, the contact area on the donor decreases as toner is removed and the contact area on the receiver increases as the particles are transferred. Approximately 80% of the toner initially on the donor was transferred by ramping the applied field to 18 V/ μm over a time interval of 2 min. More importantly, toner transfer occurs over a wide range of applied field values, from 4 to 18 V/μm. According to Eqn. (4), this behavior is a direct manifestation of the distribution in particle contact areas initially on the donor electrode. Figure 4b shows this same data plotted as the contact area change relative to the initial values at zero field. In addition, the filled circles show the difference in contact area change between the receiver and donor electrodes, amplified by a factor of 2. In all of our investigations, this difference is nonzero throughout most of the applied field range, indicating that, in general, toner particles change their contact area when transferred. In Figure 4b, the contact area difference is positive for fields up to 17 V/μm, implying that particles transferred in this field range have, on the average, smaller contact areas on the donor electrode than when they attach to the receiver. This is consistent with the notion that toner particles with the lowest adhesion (ie smallest areas of contact) are removed from the donor first, landing on the receiver with a new (higher) average contact area. The reverse is seen for fields above 17 V/μm, where the particles with the highest adhesion (largest contact area) were detached and transferred. The detachment process is thus selective based on contact area, while the transfer to the receiver produces a randomizing effect on a particle's area of intimate contact with the substrate.

Dependence of Adhesion on Initial Toner Coverage

For toner coverages less than a monolayer, one would not expect the adhesion of particles to depend on the coverage according to the model of Eqn. (2). (In contrast, the simple electrostatic image force model of Eqn. (1) predicts an increase in toner adhesion with increasing coverage, due to dipole electric fields from neighboring particles.[11] To investigate this effect, a series of transfers was performed in which the initial (sub-monolayer) toner coverage on the donor electrode was varied systematically from 0.1 to 0.9 mg/cm^2. Adhesion data for three representative coverages is shown in Fig. 5, where the contact area on the receiver is plotted against that on the donor, both normalized to A_0, the initial contact area on the donor electrode. This compressed format greatly facilitates the simultaneous comparison of data from several transfers. If there is no change in contact area during toner detachment and transfer, the data in Fig. 5 should follow the dashed line of slope = -1. Any deviation above this line represents an increase in contact area upon transfer, while the converse is true for data below it. The data from Fig. 4 is shown with the solid circles in Fig. 5. The high coverage adhesion data falls above this and never crosses the dashed line, while for low coverage the data remains close to the dashed line and crosses it much earlier in the transfer process. (The direction of increasing field is from right to left.)

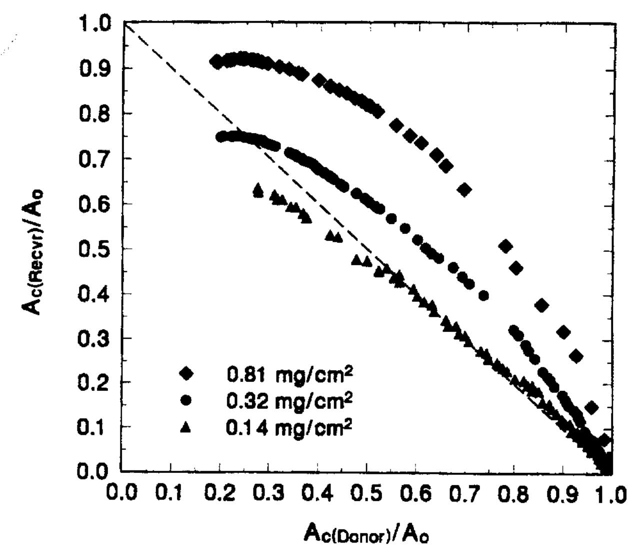

Figure 5. Plots of toner contact area on the receiver electrode vs. toner contact area on the donor, for 3 initial donor coverages. For each curve, all values are normalized to the initial contact area on the donor, A_0.

These results strongly suggest that the average contact area for particles on the donor plate decreases as the initial coverage is increased. For light coverages, the particles are isolated and able to optimize their contact areas solely on the basis of their shape and orientation as they are initially deposited on the donor electrode. As more particles are deposited in the initial loading, some are prevented from assuming their optimal orientations (maximizing their contact area) by other neighboring particles. This effect produces more low contact area particles for heavier depositions, particles which will be removed more easily and which will show a greater relative increase in contact area as they arrive on the receiver electrode.

According to Eqn. (4), another metric of toner adhesion is the applied field required to transfer 50% of the toner to the receiver. For the series of transfers discussed above, this median transfer field dropped monotonically from 15 V/μm at the lowest coverage investigated (0.14 mg/cm^2) to 6.9 V/μm for a coverage of 0.81 mg/cm^2, a change of more than a factor of two. Calibration curves for the donor electrode, which measure contact area as a function of toner coverage, support the interpretation that the reduced adhesion for higher coverages is in fact due to a reduction in the average contact area. The coverage was measured by weighing the donor electrode before and after each toner deposition. For coverages above 0.25 gm/cm^2, the data begin to fall short of the linear trend seen at lower coverages, indicating reduced average contact area for toner particles which arrive later in the deposition of denser layers. Scanning electron micrographs show that second layer particles are present in these depositions, but their number is too small to account for this effect.

Discussion and Conclusions

Our results emphasize the role of toner contact area in adhesion. However, the relative strengths of the electrostatic and non-electrostatic terms in Eqn. (2) have not been addressed here. We are currently investigating this issue by comparing the adhesion of toner samples in which σ, the surface charge density on the particles, is varied. To vary only σ and leave the total charged area on the particles (and thus the ratio $f = A_c/A_t$) constant, it is necessary to change the triboelectric properties of the carrier beads by using different carrier coatings. According to Eqn. (4), it should be possible to determine which of the two terms is dominant by noting the changes in adhesion resulting from variations in σ.

The focus on toner contact area in this work stems directly from the experiments suggested by the charge patch model of toner adhesion. The techniques we have used, based on total internal reflection, allow measurements of particle contact area as a function of applied electric field and support the predictions of the charge patch model. For a given toner sample, our measurements indicate that the adhesion is governed primarily by the contact area of toner particles with a surface. It is conceivable that there may also be some selectivity of toner particles based on size and/or charge during electric field detachment and transfer. However, from charge spectrograph and size distribution measurements of the transferred particles, performed at selected field values along the transfer curve, there is no strong preference seen for detaching particles based on their charge or size; what matters is toner contact area with the electrode surface.

The discovery of significant variations in adhesion as a function of coverage underscores the correlation of adhesion with contact area. Our adhesion data and electron micrographs both indicate that it is the hindrance caused by neighboring particles which causes the decrease in average contact area as the deposition of particles proceeds. These observations contradict theoretical calculations which predict that the induced image force for a single particle is enhanced by as much as a factor of 6 due to neighboring particles in the toner layer.[11] This disagreement is representative of the differences between the earlier models which treat toner particles as uniformly charged spheres and the model of Eqn. (2). The charge patch model successfully accounts for the non-uniformity in shape and charge distribution in a simple manner which is consistent with a large body of experimental data on charged particle adhesion.

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