Toner Charge and Environmental Interactions with Toner Adhesion

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Abstract

Understanding charged particle adhesion forces is a critical step in the understanding and modeling of electrophotographic printing processes. Electrostatic and mechanical (Van der Waals) forces are both significant contributors to toner adhesion to substrates, and previous work has shown these to have roughly equivalent magnitudes in modern printer designs. Measuring distributions of toner adhesion as a function of multiple parameters including environmental and toner charge variation has revealed that there are additional interactions beyond Coulombic Attraction and dipole induced London-Van der Waals' forces which are significant contributors to system performance. A model for toner adhesion is presented, including a term which describes the increased adhesion resulting from particle deformation at higher temperatures. Experimental results show good correlation to the model.

Introduction

There has been controversy as to the relative roles of Coulombic and dipole induced mechanical attraction in the development and transfer of toner [1]. Measurements of toner adhesion have shown that toner, not covered with surface additives to reduce adhesion (EPAs), were highly adhered to a variety of substrates, more varied in their adhesion and less dependent on toner charge [2,3]. The size of toner also has an impact on toner adhesion with smaller toner more critically impacted by non-charge dependent forces [1,4]. Understanding toner adhesion has been hindered by the difficulty in measuring a distribution of toner adhesion for actual printing systems.

The recent development of a toner adhesion measurement tool based on an air jet to remove toner and optical measurements to quantify that removal distribution has allowed for a new level of testing of the factors contributing to toner adhesion [5]. The tool has been used to quantify toner adhesion in actual printing systems including on photoconductors and transfer belts, and under a variety of actual printing conditions. The initial results of this tool coupled with scanning electron microscope analysis of high and low adhesion toners confirmed that contact area, either reduced due to EPA loading or increased due to toner damage in transfer, had a significant impact on toner adhesion and therefore toner performance. Additionally, the range of adhesion forces for toner on a transfer belt in current electrophotographic printers ranged from less than 10nN to over 1000nN within one sample. Within those samples the toner mid to low adhesion forces were quite predictable when particle charge was known.

Actual printing systems provide a variety of challenges to the development community as they are required to perform well under a wide range of environmental and other operating conditions. Measuring key parameters, such as toner adhesion, under actual printing conditions yields an understanding of actual process mechanisms. That understanding, in turn, should lead to better product design and performance.

The Two-Term Model

The controversy surrounding toner adhesion has centered on the assumption that there are two key mechanisms contributing to toner adhesion to any substrate. These two forces are the long range Coulomb attraction/repulsion forces and the close range dipole forces; also known as Van der Waals forces, London-Van der Waals forces or dispersion forces [1]. These forces act both between particles and between particles and substrates, and are complicated by the application of external fields for development and transfer and by the non-uniformity of charge on the toner [3,6,7]

The first of these mechanisms is the long range Coulomb attraction/repulsion forces. The attraction force between two charged particles at a distance is known to be a function of the charges on the two particles and the distance between them. Known as Coulomb's law or Coulomb's inverse square law, it suggests that at a reasonable distance the force between two particles not on a substrate would be:

$$\mathbf{F=k_e\,(q_1\,q_2)/r^2} \tag{1}$$

Where:

- $k_e = 1/(4\pi\varepsilon_o)$; ε_o the permittivity of free space = 8.854E-12 F/m
- q_1 and q_2 are the charges on the two particles
- r is the distance between two particles

Coulomb's law defines these electrostatic distance forces to be a function of the square of the charge, so any term in an adhesion equation resulting from these forces should also be a function of the square of the charge. This was then used to predict a close range Coulomb attraction between a toner particle and an oppositely charged "image" of the toner particle which is the result of polarization of and/or conduction in the substrate. The distance between the two particles can be replaced by the diameter of the toner that represents the mathematical offset between a charge at the center of the uniformly charged toner and an opposite charge at the theoretical center of the image. An additional proportionality, α, was added to reflect the polarization of the particle base material making this force material dependent. [8]

$$\mathbf{F_I} = \text{Image force} = \boldsymbol{\alpha\ q^2/(4\pi\varepsilon_o d^2)} \tag{2}$$

Where:

- d is the toner particle diameter
- q is the toner particle charge

When applied to toner on a dielectric substrate, Coulomb's law can be used to describe the attractive force between charged toner and the image area created by charge separation in the dielectric substrate. This image charge area is complicated by the presence of multiple toner particles in close proximity [9]. It is convenient

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to refer to these forces as electrostatic forces as they are a function of the charge of the particle.

When particles "touch", meaning that the distance between adjacent molecules is on the order of a few hundred angstroms, intermolecular forces come into play that greatly enhance adhesion. These intermolecular forces are thought to be a result of dipole interactions of the materials involved and are a function of material properties and contact area as given by the Johnson-Kendall-Roberts (JKR) equation [10].

$$\mathbf{F_{Van\ der\ Waals} = -3/2\ W_a\ \pi\ R} \qquad (3)$$

Where:

- $\mathbf{W_a}$ is the work of adhesion
- **R** is the radius of toner particle

Given a printer system with a constant toner, environment, speed, and field parameters, the adhesion of toner to a substrate like a transfer belt would be expected to be a function of electrostatic and mechanical forces.

$$\mathbf{F_a = F_{Van\ der\ Waals} + F_{electrostatic} = A + Bq^2} \qquad (4)$$

When charge is in Coulombs x 10^{-15} and diameter is in microns the units will cancel so that $B \cong 2.5$ depending on the specific toner diameter. Kemp [9] presented a more exact relation between charged multi-particles, and that suggests that the coefficient "B", and the other electrostatic coefficients, should be a number between 0 and 1 for the electrostatic portion of the attraction. As has been reported in the literature, the actual values of F_a measured are about an order of magnitude higher than theoretically predicted by electrostatic attraction.

In a two transfer system it is possible to change the charge on toner entering the second transfer nip by changing the voltage applied at successive first transfer stations down stream of the initial transfer. This allows the charge to be changed independently of other variables allowing for adhesion data that separates Van der Waals and electrostatic parts. Figure 1 shows a graph of toner adhesion as a function of toner charge that was created in this way. The environment was held at 60°F, 8% relative humidity and the samples were taken from toner that had been transferred to an intermediate belt just before it entered a second transfer nip. Each measurement produced a distribution of adhesion, and the force for 50% removal is shown. Superimposed on that data is a theoretical curve using the format described in equation (4), where A=50nN and B=7.0. In this theoretical prediction, A=50nN would represent the mean Van der Waals adhesion force for the samples. The slope factor on the charge squared term, B=7.0, contains within it a combination of the constants in Coulomb's law, the diameter of the toner which in this case is taken at about 6 µm, and the interaction of multiple charged particles in a given area. The additive effect of multiple particles on adhesion has been discussed as the image forces from other particles in close proximity should be additive. Those particles in a pile that are in closest proximity to the base material will experience the strongest effect and those in the center and top of the pile will experience the smallest. Fields from dipole effects have been sited as a multiplier of 6.95 to 6π [1,4,11].

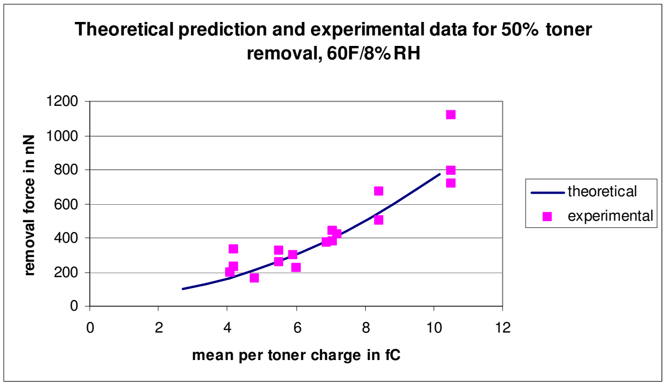

Figure 1: Median toner removal force as a function of average per-toner charge. The theoretical curve represents a two term prediction based on electrostatic and Van der Waals attractions.

The quality of fit between theoretical and experimental is acceptable although it appears that the experimental curve may be more sensitive to charge than is predicted by the two term model.

The Impact of Environment

Given the predictive equation described above, toner adhesion for the same system should be predictable at different environments. It is quite conceivable that the initial constant "A" might change as the work of adhesion changes, for example with the presence of water bridges at higher humidity. However the electrostatic portion should be a function of toner charge only. This is not what actually happens when the system is tested. Figure 2 shows data for toner adhesion to an intermediate transfer belt for three different environments 60F/8% relative humidity; 75F/40% relative humidity and 78F/80% relative humidity. For the same charge on the toner there are different adhesion values, and that difference is a function of the toner charge. The two term model can be modified to give a good general prediction of the adhesion force measured. However the model is not capable of reflecting the change in adhesion response to charge that is seen changing with environment.

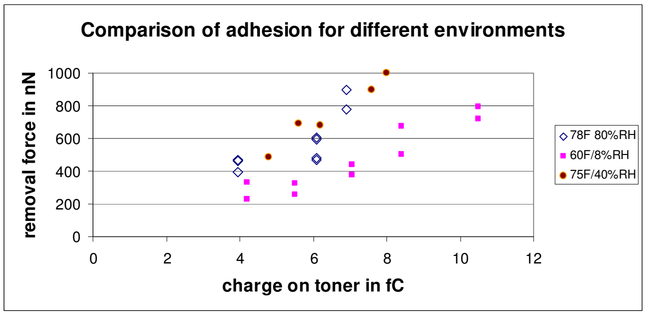

Figure 2: Data for adhesion of toner to an intermediate belt where the printer was acclimated and stopped during the printing process at each of three different environments.

The Physics of Warm Toner Transfer

The existence of a change in charge-response in different environment conditions suggests an additional physical mechanism. The first step in identifying and understanding this mechanism is to separate the temperature effect from the humidity effect to see which of these, or both, is causing the change in charge sensitivity.

Figure 3 shows the results of tests of adhesion with charge to separate out humidity from temperature effects. Toner adhesion was tested at a matrix of high and low temperatures and high and low relative humidity to determine the relative impact of each parameter. The graph shows that the data falls into two groups divided by temperature. Warm temperatures have higher adhesion than cooler temperatures across a wide range of relative humidity levels.

Water bridges under particles are frequently a source of higher adhesion with increased humidity, however a function of adhesion with relative humidity was not apparent. There are two reasons why water bridges are not likely significant in toner adhesion. The first is that the temperature of the components of a transfer system, while printing, are slightly above that of the ambient environment discouraging water condensation. Secondly, toner spends only a few seconds on the transfer belt before being transferred to paper limiting time for condensation.

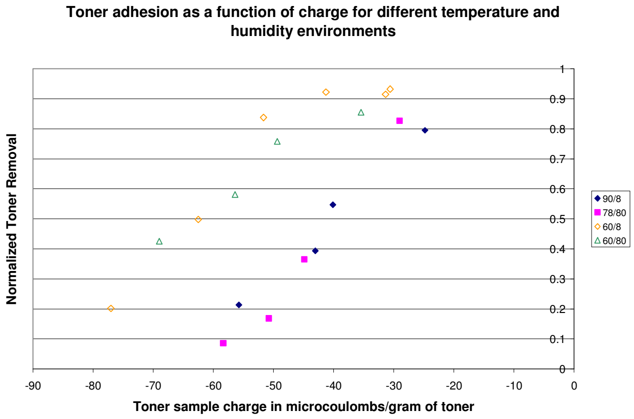

Figure 3: Data from toner adhesion testing at 90°F/ 8% relative humidity; 78°F/ 80% relative humidity; 60°F/ 8% relative humidity and 60°F/ 80% relative humidity. Data is shown as a function of toner charge for each sample, which was manipulated with transfer voltages.

There are several possible mechanisms for heat to impact toner adhesion. If temperature simply made toner more mechanically adhesive, the expected outcome would be a curve with the same sensitivity to charge, but a higher offset. There is an offset difference seen in the data above, suggesting that potentially the "wet-ability" of the material could be changing with temperature. This offset can be compensated for by altering the coefficient A in the two-term model. Coefficient B should not be sensitive to changes in material properties. As a result the slope of the data should remain the same. This is not the change seen in the data in figure 2.

Another potential mechanism could be the heat causing a small relaxation in the toner particle resulting from a change in modulus of elasticity. A decrease in toner modulus would cause a small deformation of the particle as electrostatic forces pulled it toward the transfer belt. This could change the adhesion of the toner to the substrate in two ways. The first mechanism would be the decrease in distance between the toner and its image charge. The second mechanism would be an increase in contact area caused by the modest deformation.

In 2006, Jurgen Thomas published his PhD dissertation on the Mechanics of Particle Adhesion. [12]. Thomas' work describes the deformation of a particle under the pull of gravity. Using his work and substituting the Coulombic attraction for gravity one can make an estimate of the relative potential contribution of each of these mechanisms. If the modulus of elasticity were to drop by half, the relative change in the height between two dipoles would be only 0.001 µm. That small of a change does not make any measurable impact on Coulomb attraction. The same change in height would make a difference in the radius of the contact area from 0.04 µm to 0.05 µm. This change makes the difference in contact area increase by 62% which will have a significant impact on adhesion. The normal force on a particle from the substrate is a function of Coulombic attraction, which is a function of toner charge squared. The adhesion measured by rolling resistance is a function of the normal force to the 3/2 power. Inserting a charge squared term in for normal force yields a pull off force that is sensitive to the charge of the toner cubed.

The first order impact of the adhesion of a particle as a function of the modulus of elasticity has been suggested many times [12] Actual changes in toner modulus with temperatures lower than the toner softening point are not readily available, but the hardness of the material is not a step function. The gravitational force on a 6µm toner particle is roughly 0.0013nN, where as the dielectric pull from a -20 µC/g, 6µm diameter toner particle on a substrate would be 17nN which is much more significant and is therefore the key contributor to the footprint of the toner on the substrate.

Comparison to Experimental Data

Examining adhesion of toner at different environments sheds light onto the actual physics of particle adhesion. The proposed model is now a cubic polynomial based on this work and the work described by B. A. Kemp [9].

$$\mathbf{F_a = A + Bq + Cq^2 + Dq^3} \qquad (5)$$

Where:

- A represents the Van der Waals attraction forces
- Bq represents the additional force due to non-uniform charges [15]
- Cq^2 represents the actual Coulombic attraction arising from multiple particles
- Dq^3 represents the Van der Waal attraction that is a function of the toner footprint from the Coulombic attraction forces

In reviewing this model, only the A and D coefficients are likely to change as a function of temperature. Coefficient A can change as toner or the substrate can change wet-ability with increased molecular energy. Coefficient D can change as the modulus of elasticity drops as the material softens slightly with temperature. If this model is capturing the main features of the physics, it should be able to track the change seen across environments. Figure 4 shows the experimental data with theoretical warm and cold curves.

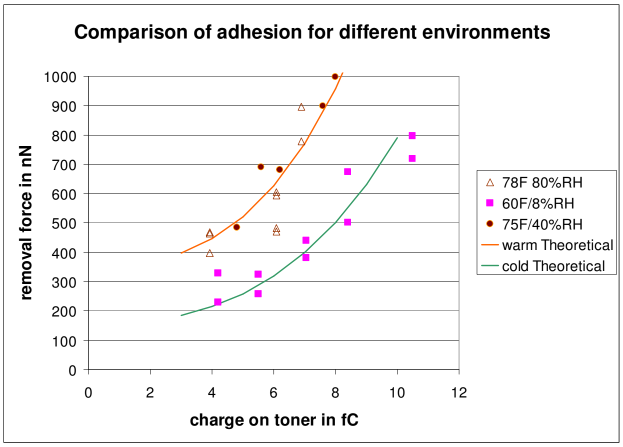

Figure 4: Adhesion data for toner on a stopped intermediate belt immediately following printing at different environments. The two theoretical curves show the difference in curvature with charge as a function of the environment.

For the warm curve shown in figure 5 the coefficients of equation (5) are: A=350nN, B=4.0 indicating the effect of non-uniform charge, C=1.0 (for the Coulomb attraction) and D=1.0. For the cold curve the coefficients are: A=150nN, B=4.0, C=1.0 and D=0.5. Non-uniform charge was enhanced in all of these data sets due to the manner in which the higher charge samples were obtained – namely increasing transfer voltage downstream of the initial transfer station to shower the toner with charged ions.

Different toner designs and different transfer belt substrates will yield different values for these coefficients. However warmer ambient environments always lead to an increase in adhesion over cold environments for any toner charge level.

Conclusions

Toner adhesion to an intermediate transfer belt in a printer is increased with increasing temperature, but is not strongly impacted by relative humidity. The toner adhesion also has a different response to toner charge for different temperatures that is not predicted by the traditional sum of Van der Waals and Coulomb Attraction models. Temperature likely impacts the molecular wet-ability of the toner, while it also slightly softens toner making it more susceptible to deformation under load. Charge on the toner surface is the main loading on toner. Increased toner charge will have a stronger impact on contact area in a warm environment than in a cool one. The increase in contact area with toner charge results in a proposed additional cubic function of the toner charge term, to compensate the adhesion model.

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