The Adhesion of Spherical Toner Particles to an Organic Photoconductor: Contributions of van der Waals and Electrostatic Interactions

S. Cormier, D. S. Rimai* and D. J. Quesnel***
**NexPress Solutions LLC., Rochester, New York*
*** University of Rochester, Rochester, New York*

Abstract

The forces needed to remove monodisperse spherical toner particles from an organic photoconductor were determined using electrostatic detachment for a series of particles having diameters between 2 μm and 12 μm. It was found that the removal force varied linearly with particle radius, as predicted by JKR (K. L. Johnson, K. Kendall, and A. D. Roberts, Proc. R. Soc. London, Ser. A **324**, 301 (1971). This result is inconsistent with the predictions of models that assume that the detachment forces are dominated by either a uniform charge distribution over the surface of the particle or localized charged patches. Moreover, reasonable works of adhesion are obtained if one assumes that the removal forces are dominated by surface, rather than electrostatic, forces. These results seem to suggest that, for spherical toner particles in this size range, adhesion is dominated by van der Waals interactions.

Introduction

The adhesion of toner to photoconductors in dry electrophotographic processes has long been a topic of interest and whose importance is growing with decreasing toner size.[1-14] Indeed, a fundamental understanding of toner adhesion is important, not only for controlling transfer of toned images from the photoconductor to a receiver, but also in terms of cleaning and image quality. More specifically, it has been long known that the process of transferring toner electrostatically becomes more difficult as the size of the toner decreases. This can result in a decrease, rather than an increase in image quality, with decreasing toner diameter, as evidenced by the occurrence of mottle and hollow character (the failure to transfer the centers of fine lines).

An added complication is that, as transfer efficiency decreases, it is necessary that more toner be removed from the photoconductor by the cleaning system. However, the smaller toner tends to be more difficult to remove than the larger toner.[15] Both of these effects can stress the cleaning system. Moreover, inefficient transfer can lead to increased operating costs because more toner needs to be deposited on the photoconductor to compensate for the toner that does not wind up on the receiver.

It is commonly believed that toner to photoconductor adhesion is dominated by either electrostatic forces, due to the charge on the particle interacting with an induced image charge in the photoconductor, or electrodynamic forces, such as those giving rise to van der Waals interactions. Indeed, much of the research in this area that has been conducted over the past two decades has been aimed at determining the nature of the interactions. Despite all the interest in toner to photoconductor adhesion, the experimental results appear to be contradictory

There are several reasons for the diversity of proposed toner adhesion mechanisms. Certainly, the variations in toner size – from about 3 μm to 99 μm- obviously can be responsible for much of the apparently contradictory results. In addition there appears to be a theme in the literature that leans to an either-or scenario, *i.e.* the interactions are either electrostatic or van der Waals. In fact, both forces are present.

Much of the discrepancy arises from experimental difficulties. Specifically, polydispersity in toner size and shape complicate attempts to analyze data. Indeed, the dependence of the separation force on toner size may shed more light on the mechanisms controlling toner adhesion than measurements on individual batches of toner. Finally, as is often reported in the literature, there is a temporal dependence to the toner adhesion, with toner generally becoming more tightly bound to the photoconductor over time. However, separation force measurements, including centrifugation and electrostatic detachment, are generally quite time intensive.

In this paper we report real-time separation force measurements of a series of monodisperse spherical toners, having diameters between 2 μm and 12 μm, from a commercially available organic photoconductor.

Experiment

The force needed to separate monodisperse, spherical, polystyrene toner particles from an organic photoconductor was measured using electrostatic detachment in real time, using an electrostatic transfer station.

A series of black, polystyrene, monodisperse toner particles having diameters between approximately 2 μm and 12 μm were made using the method of Ugelstad,[16] as modified by Hoskyns.[17] In addition, classified spherical polyester toners were formed by dissolving the toner material in dichloromethane and spray drying.

Developers were prepared by mixing a predominance of once size toner with a few percent by weight of the next larger size particle. For example, a developer comprising principally 2 μm toner would also comprise a few percent by weight of a 5 μm toner. For the largest size toner particles studied (12 μm diameter), 30 μm diameter particles were used to establish the gap. Together, these toners would be mixed with a magnetic carrier to impart a suitable positive charge on the toner. Typical toner concentrations were of the order of 5-10% by weight of developer. In addition, the toner charge was measured from a similar developer comprising only one size of toner, assuming that the addition of the small amounts of the larger-size toner particles did not significantly alter the charge on the smaller. Toner charge was measured with a Faraday cage using samples of the toner that had been deposited on a photoconductor during the development process.

A submonolayer of toner was deposited on a polyester-based commercially available photoconductor by initially charging the photoconductor positively, and then optically discharging it to an appropriate potential. This technique was chosen so that the actual toner deposition process most closely resembles that encountered in an actual electrophotographic engine. The photoconductor was then brought into proximity with a magnetic brush development station and a uniform, submonolayer of toner was deposited using the charged area development mode.

The photoconductor was then illuminated to ensure that it was in its "conducting" mode. The receiver comprised a 4 mil thick Estar support over which was evaporated a coating of clear, electrically conducting material referred to as "chrome cermet" (chromium silicate). The receiver was gently pressed against the photoconductor during the transfer process using a roller. A DC electrical bias was directly applied to the chrome cermet layer to urge the toner to transfer. This bias was increased and the fraction of smaller toner that traversed the air gap was determined by statistically counting toner particles in representative areas of both the receiver and the photoconductor after transfer. Typically, the transfer efficiency would be measured at between half a dozen and a dozen bias levels. The fraction of particles that transferred was determined by first making a mask that allowed counting in 5 areas. Photomicrographs of both the photoconductor and the receiver were then made and the mask superimposed over the micrographs. The number of transferred and residual particles were then counted in each area. In general the counts were consistent to within a few percent. Presumably, this was due to the monodisperse, spherical nature of the particles. Toner coverage on the photoconductor was deliberately chosen to be sufficiently low so that the formation of a second layer or toner agglomeration was not a problem.

It is well known that, by coating the photoconductor with various "release agents" such as Teflon, zinc stearate, and various silicones, transfer and cleaning can be improved. In order to determine if the use of these agents decreased the toner-to-photoconductor adhesion, the force of detachment was also measured for these same toners from such photoconductors. In these cases, the release agent was generally rubbed onto the photoconductor with a cloth pad and as much as possible removed. This generally left about a monolayer-thick coating, as determined using ESCA.

Results

The use of monodisperse spherical toner particles narrowed the voltage window between transfer efficiencies of less than 10% to transfer efficiencies of more than 90% of the smaller toner particles transfer to ± 10 to 15 volts. Considering that the applied voltage was typically in the range of 300 – 350 volts, this measurement allowed a high degree of accuracy. It should be noted that this level of precision was due to the use of monodisperse spherical toner particles. In subsequent experiments that used more conventional ground toner, the transition was much more gradual. As is conventional, the force needed to separate the particles from the substrate was taken as that whereby half the smaller toner particles were electrostatically detached from the photoconductor.

The force F_E exerted on a particle with charge q, dielectric constant ε_P and radius R in contact with a substrate of dielectric constant ε_S by an applied electric field E acting through a medium of dielectric constant ε_M is given by[18]

$$F_E = -\beta q E \qquad (1)$$

where

$$\beta \approx 1 + \frac{1}{2}\left(\frac{\varepsilon_S - \varepsilon_M}{\varepsilon_S + \varepsilon_M}\right)\left(\frac{\varepsilon_P - \varepsilon_M}{\varepsilon_P + 2\varepsilon_M}\right). \qquad (2)$$

For typical polymeric materials in air, β is approximately unity. Therefore, the electrostatic detachment force applied to the smaller toner particles is simply

$$F_E \approx q\frac{V}{D} \qquad (3)$$

where V is the applied voltage and D is the diameter of the larger, spacer particles.

According to the JKR theory, the adhesion-induced contact radius a is related to the particle diameter d, the work of adhesion between the particle and substrate w_A, and any external load P by

$$a^3 = \frac{d}{2K}\left\{P + \frac{3}{2}w_A \pi d + \left[3 w_A \pi d P + \left(\frac{3}{2}w_A \pi d\right)^2\right]^{1/2}\right\} .$$

Here, K is related to the Young's moduli and Poisson's ratios of the contacting materials. It should be noted that the solutions to eqn. 5 must be real, *i.e.* eqn. 5 predicts a real contact radius as a function of toner diameter and applied force. A force tending to remove the toner from the photoconductor is equivalent to a negative load. However, the term within the square root brackets cannot be less than zero and still have a real contact radius. Accordingly, the toner must separate from the photoconductor when there is a critical electrostatic force P_S applied to the toner such that

$$P_S = \frac{3}{4}w_A \pi d .$$

Because the field generated by the charged toner particle changes as a result of the deformations resulting from the electrostatic and surface force interactions between the toner particle and substrate when the two are in contact, the actual determination of the separation field is difficult to calculate and is beyond the scope of this paper. However, if one assumes that the perturbation of the field due to the deformations is small, then

$$P_S = -\beta q E_S + \frac{\alpha q^2}{4\pi \varepsilon_0 d^2} + \gamma \pi \varepsilon_0 d^2 E_S^2 = \frac{3}{4} w_A \pi d .$$

If one further assumes that there is intimate contact between the toner and photoconductor with a sufficiently large contact area, so as to exclude any intervening medium, and that the dielectric constants of the toner and photoconductor are similar (implying that $\alpha = \beta = 1$, $\gamma = 0$), then the applied electrostatic separation force F_E^S is simply

$$F_E^S = \frac{3}{4}\pi w_A d + \frac{q^2}{4\pi \varepsilon_0 d^2}$$

and the corresponding separation field E_S is given by

$$E_S = \frac{3}{4} w_A \pi \frac{d}{q} + \frac{q}{4\pi \varepsilon_0 d^2} .$$

If it is assumed that the surface charge density σ is approximately constant, then

$$F_E^S = \frac{3}{4}\pi w_A d + \frac{\sigma^2 \pi d^2}{4\varepsilon} .$$

The total separation force was found to vary linearly with toner diameter, suggesting that surface forces dominate over electrostatics. The work of adhesion was calculated to be approximately 0.01 J/m^2.

Release agents such as various silicones, Teflon, and zinc stearate have often been coated onto photoconductors to improve transfer and facilitate cleaning. Each of these materials was observed to decrease the detachment force, with silicone showing the least benefit and zinc stearate having the greatest effect, reducing the toner to photoconductor adhesion by almost a factor of 3. It should be noted that these measurements were made using the same developers. Had the toner adhesion been dominated by the electrostatically induced image forces, these release agents would be expected to have minimal effects on the separation forces.

If toner adhesion were dominated by surface, rather than electrostatic, forces, it would be expected that the materials comprising the toner would be expected to effect adhesion. Indeed, it was found that the polyester toner was significantly more adhesive that is the polystyrene. The work of adhesion calculated for the polyester toner is 0.019 J/m^2, or almost twice that of the polystyrene toner, even though the charge on comparable size polystyrene toner was higher. Again, this argues that some material property other than its charge dominates the detachment force.

Conclusions

The force needed to remove spherical toner particles having diameters between approximately 2 and 13 µm from an organic photoconductor, measured using electrostatic detachment, was found to vary linearly with toner diameter. Moreover, it was also found that various release agents such as silicone oil, Teflon, and zinc stearate, also reduced the force needed to separate the toner from the photoconductor. Finally, it was necessary to apply a stronger force to remove polyester toner particles from the photoconductor than it was to remove polystyrene toner. The electrostatic contribution to the total adhesion force was found to be small compared to the surface forces. However, this contribution was found to increase with increasing toner diameter, suggesting that the adhesion of very large toner particles (*i.e.* those with diameters greater than about 50 µm) may be dominated by electrostatic forces. The results of this study suggest that, in order to understand the nature of the interaction between toner particles and the photoconductor, one must pay particular attention to factors such as toner charge and toner particle size.

References

1. V. M. DePalma, *Photographic Sci. Engin.* **26**, 198 (1982).
2. N. S. Goel and P. R. Spencer, *Polymer Sci. Technol.* **9B**, 763 (1975).
3. D. A. Hays, *Photographic Sci. Engin.* **22**, 232 (1978).
4. D. A. Hays and W. H. Wayman, Inst. Phys. Conf. Ser. No. 66: *Electrostatics*, pp. 237-242 (1983).
5. D. A. Hays and W. H. Wayman, *J. Imag. Sci.* **33**, 160 (1989).
6. E. A. Eklund, W. H. Wayman, L. J. Brillson, and D. A. Hays, *IS&T's Tenth International Congress on Advances in Non-Impact Printing Technologies*, pp. 142-146 (1994).
7. C. J. Mastrangelo, *Photographic Sci. Engin.* **26**, 194 (1982).
8. L. Nebenzahl, J. Borgioli, V. De Palma, K. Gong, C. Mastrangelo, and F. Pourroy, *Photographic Sci. Engin.* **24**, 293 (1980).

9. D. A. Hays, in *Advances in Particle Adhesion*, D. S. Rimai and L. H. Sharpe (eds.), Gordon and Breach Publishers, 1996, pp. 41-48.
10. B. Gady, R. Reifenberger, D. S. Rimai, and L. P. DeMejo, *Langmuir* **13**, 2533 (1997).
11. D. K. Donald, *J. Appl. Phys*. **40**, 3013 (1969).
12. D. K. Donald and P. K. Watson, *Photographic Sci. Engin*. **14**, 36 (1970).
13. M. H. Lee and A. B. Jaffe, in *Particles on Surfaces 1: Detection, Adhesion, and Removal*, K. L. Mittal (ed.), Plenum, New York City, 1988, pp.169-178.
14. B. Gady, D. J. Quesnel, D. S. Rimai, S. Leone, and P. Alexandrovich, *J. Imag. Sci. Technol*., in press (1999).
15. V. M. DePalma, *Photographic Sci. Engin*. **26**, 198 (1982).
16. J. W. Vanderhof, M. S. El-Aasser, and J. Ugelstad, U. S. Patent #4,177,177 (1979).
17. W. Hoskyns, private communication (1982).
18. D. S. Rimai and D. J. Quesnel, *Fundamentals of Particle Adhesion*, Global Press, Moorhouse, 2001.

Biography

Steven O. Cormier, NexPress Solutions LLC. Steven O. Cormier received his AS (machine design) from Worcester Junior College and his BS (mechanical engineering) from Central New England College of Technology, and is presently an advance development engineer for NexPress Solutions LLC. Mr. Cormier conducts research and development in the areas of mechanics, materials and Electrophotography.