Characterization of Toner Adhesion to Carrier: A Phenomenological Model

James C. Maher
Eastman Kodak Company, Rochester, New York

Abstract

In the two component electrophotographic development process toner is delivered to the latent image via a complicated interaction of electrical and mechanical forces. The force of adhesion between the toner and carrier must be overcome during development to allow the charged toner to be influenced by the imaging field. The development efficiency, i.e., the degree to which the latent image is developed at a given process speed, is governed by the net charge distribution in the developer mass and the availability of toner. Determining which is dominant is difficult experimentally in a full process mode. This paper introduces a methodology for characterizing toner to carrier adhesion using an off-line device that agitates the developer in the same fashion as the full process. Using spherical toners with carefully controlled particle size distributions, a characteristic time constant for toner release can be measured and used for comparative purposes. A phenomenological model is also proposed to explain the experimental results.

Introduction

The small particle development (SPD) process, as described earlier by Miskinis,[1] and used in the later model Kodak copiers and duplicators, was a major step forward in image quality enhancement and improved development efficiency. SPD is a two component process utilizing small (30µm) permanently magnetized ferrite carrier particles and conventional toner. The developer is delivered to a toning roller consisting of a rotating shell internal to which is a segmented rotating magnet structure. The developer forms a chain in response to the magnetic field and the chain flips as the magnets rotate. As a result the developer walks across the surface of the toning roll in a direction opposite to the rotational direction of the magnets (Figure 1). The flipping process provides agitation that frees toner from the carrier.The small carrier provides a larger net surface area for tribocharging, thus allowing a higher toner concentration and also provides a more uniform local field for development.

Characterization of such a complicated process can be difficult and does not yield readily to off-line predictive testing. The purpose of this paper is to describe an experimental method for separating development mechanisms and looking only at the adhesion characteristics of the toner to the carrier as well as the subsequent liberation of the toner particles. Toner adhesion in electrophotographic developers has been widely studied but the experimental methodologies typically do not factor in the mechanical agitation that is experienced in the actual development zone.
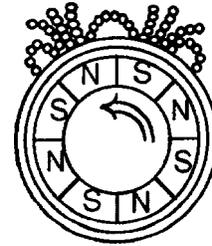

Figure 1. Schematic diagram of the SPD process. Permanently magnetized carrier walks across the surface of the toning roll as the magnets rotate.

Experimental

The experimental device[2] (Figure 2) that was used for this work is a planer embodiment of the SPD process. It consists of two plane parallel non-magnetic electrodes, with a 1.0 cm separation. The bottom electrode is connected to a variable voltage source, while the upper electrode is connected to an electrometer. In close proximity to the bottom electrode is a segmented magnetic donut. The magnet rotates in a plane parallel to the electrode. The response of the developer sample as the magnets rotate is very similar to what occurs on the toning roll, the carrier will flip and walk around the ring defined by the magnetic field. Applying a potential difference between the electrodes with the field in the proper direction will pull the toner across the gap as it becomes free of the carrier. The integrated charge on the toner that is transported across the gap is registered by the electrometer. The mass of the toner was measured by weighing the upper plate and a charge to mass ratio was calculated.
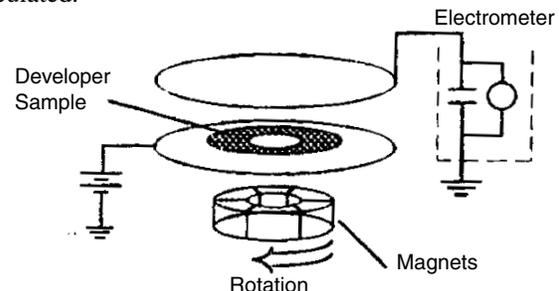

Figure 2. Experimental apparatus used to emulate the action of the SPD developer on the toning roller.

If space charge and gravity are ignored the equation of motion of a toner particle once it is liberated is:

$$m_T \frac{d^2x}{dt^2} = q_T E - 6\pi\eta r_T \frac{dx}{dt} \qquad (1)$$

where m_T, q_T, and r_T are the mass, charge, and radius of the toner particle, E is the applied field, η is the viscosity of air, and "x" is in the direction of the applied field. Using an applied field of lKV/cm, a q/m of 20μC/gm and a toner radius of 5μm equation (1) predicts a transit time of the order 160 msec. Experimentally the time to strip all of the toner out of the agitating developer mass is of the order of tens of seconds or longer depending on the nature of the developer. This means that the toner spends the majority of its time freeing itself from the developer. As the carrier and toner collide with each other and with the lower plate there is a finite probability that toner will obtain enough mechanical energy in concert with the local applied field to free itself of the carrier. Hays[3] and Schmidlin[5] have most recently referred to the roll of adhesion in magnetic brush development but they both refer to wide ranges of adhesive forces that the toner particles experience due to large variations in size and shape.The electrostatic force of adhesion is typically modeled as the image charge force for a perfectly spherical particle but the calculations are always orders of magnitude less than are actually measured.[4-8] Hays[4] has proposed a "Toner Charge Patch" model to account for the large measured force of adhesion and attributes the force to the localized charge patterns on irregular particles. For this series of experiments batches of toner particles were prepared that were nearly perfectly spherical with a very tight particle size distribution to try to side step some of these issues.

The experimental approach was designed to look at the time necessary to fractionally remove the toner from the agitating developer mass. This was done by running the magnets with the field applied for a set period of time shorter than the time required to strip all of the toner and measure the rate at which mass and charge are transferred to the upper plate. It was verified that there was a minimal amount of wrong sign toner and that the magnet strength was sufficient to prevent wrong sign carrier from transferring to the upper electrode.

Results

When the toner mass data is manipulated and plotted against time as in Figure 3 it suggests that the arrival of toner at the upper plate can be predicted by the following relationship:

$$m_T(t) = M_T \left\{ 1 - \exp - \left(\frac{t}{\tau} \right) \right\} \qquad (2)$$

where $m_T(t)$ is the toner mass on the upper plate at any time "t", M_T is the total toner mass in the sample, and "τ" is a characteristic time constant. Interestingly this relationship was consistent across all experimental developers that were investigated. Rimai, et al.,[9] have noted the same development behavior in their investigations of novel development sensors on actual toning rollers. The parameters that determine the value of "τ" were of interest because this is a measure of how easy it is to liberate toner during the development of a full process latent image.

The Dependence of "τ" on Agitation Rate, Electric Field, and Q/M

Using "τ" as the response, a central composite designed experiment[10] was conducted using agitation rate and elec-

tric field as the experimental control factors. The agitation rate was varied by controlling the speed of the rotating magnets. Figure 4 is a design space plot illustrating how "τ" varies in response to the applied field and magnet speed. The response to the agitation is much stronger than the response to the applied field. This is not a particularly surprising result since the applied fields are not strong enough to strip toner out of the sample without some degree of agitation. The field is not effective until the impact forces overcome the short range adhesive forces. Still, the response to the field is not trivial and may be attributed to the reduction of the Coulombic barrier as proposed by Donald and Watson.[11]
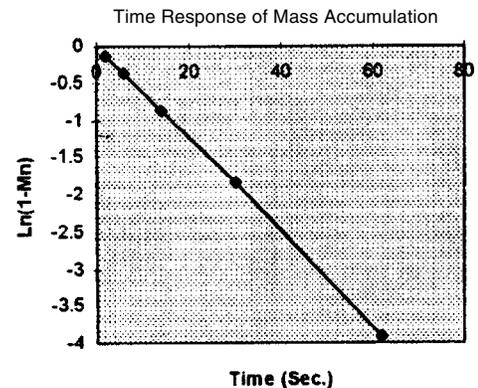

Figure 3. The natural log of (1-Mn), where Mn is the mass of toner arriving at the upper plate normalized to the total mass of toner in the sample, as a function of agitation time
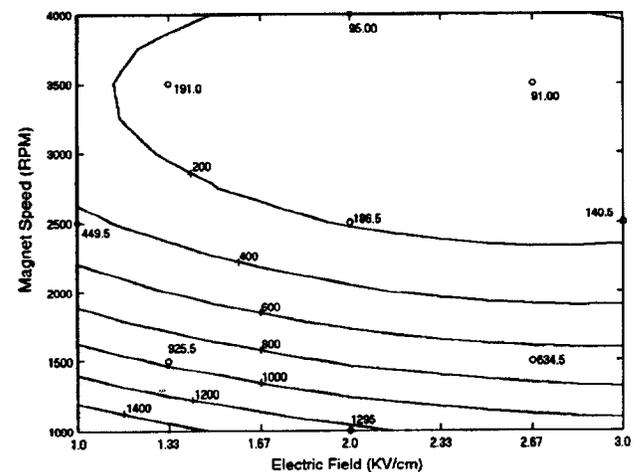

Figure 4. Results of central composite experiment shown on a design space plot. Each circular point in the space corresponds to the time constant measured at the parameter setpoints, the contour lines correspond to the predictive model.

Following this rationale an experiment was designed to determine the role of toner charge on "τ". There are two ways to vary the toner charge; change the charging characteristics of the toner or change the characteristics of the carrier surface. For the following experiment each was done. Two batches of toner were prepared with the only difference being charge agent, one designed to be high charging and the other designed to be low charging. In addition two batches of carrier were prepared with different

surface coatings, once again each designed to give a different level of charging. The results of a two level full factorial experiment comparing the two toners and carriers are presented in Table 1. These data clearly shows that the time constant has a strong dependence on the toner charge.

Table 1. Results of a full factorial experiment with the same base toner and carrier but with carrier coatings and charge agents with different charging characteristics mixed into four developers.

Developer Number	Carrier Charge	Toner Charge	Toner Q/M(μC/gm)	Time Const. (sec.)
1	Lo	Lo	60	13
2	Lo	Hi	78	30
3	Hi	Lo	82	22
4	Hi	Hi	130	81

Discussion

It is clear from the experimental observations and calculations that the observed time constant is a measure of the time it takes for a toner particle to free itself from the developer mass. It is impossible to tell whether the toner particles are oscillating between carrier particles and the measurement is of the characteristic time it takes to be ejected from the sample or if the toner particle can escape as soon as it is free of the carrier particle. It is more than likely a complicated combination of both but if the latter mechanism is dominate the following argument can be proposed. Consider the probability distribution of the impact force on a toner particle as it is tossed about in the development zone. Figure 5 would not be an unreasonable representation of what this distribution might look like.
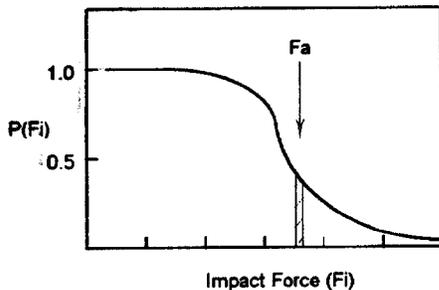

Figure 5. Probability distribution of the impact force that a toner particle experiences as it is agitated. F_a is the force of adhesion to the carrier.

Obviously the lower the impact force the higher the probability that the toner particle would experience it in the turmoil but the force of adhesion to the carrier is greater and the toner remains attached. There is always a probability that the particle will experience a situation where the impact force matches or exceeds this force of adhesion, called F_a in Figure 5. If the average time between these events is "τ" the number of collisions "n" a toner particle would experience in a time "T" where the impact force is greater than F_a would be:

$$n(t) = \frac{T}{\tau} \tag{3}$$

The probability that a toner particle would experience this force in a time "dt" would be:

$$P(F_a)\big|_{dt} = \frac{dt}{\tau} \tag{4}$$

The number of toner particles "dN" that experience a collision with an impact force greater than "F_a" in a time "dt" will be:

$$dN = N(t)\frac{dt}{\tau} \tag{5}$$

where "N(t)" is the total number of toner particles present at time "t". Since it is the mass of toner that is measured and the mass is the product of "N(t)" and the mass of one toner particle equation 5 can be rewritten as:

$$dm(t) = m(t)\frac{dt}{\tau} \tag{6}$$

During agitation in the presence of an electric field the amount of toner left in the sample after a time "t + dt" will be:

$$m(t+dt) = m(t) + \left(\frac{dm}{dt}\right)dt = m(t) - m(t)\frac{dt}{\tau} \tag{7}$$

which, after rearranging, becomes:

$$\frac{dm(t)}{dt} = -\frac{m(t)}{\tau} \tag{8}$$

The solution to equation 8 is:

$$m(t) = m(0)\exp\left(-\frac{t}{\tau}\right) \tag{9}$$

where m(0) is the original mass of toner in the sample. The mass that is measured experimentally is the mass that leaves the sample or "m(0)m(t)". Calling that mass m′(t) we have:

$$m'(t) = m(0)\left(1 - \exp\left(-\frac{t}{\tau}\right)\right) \tag{10}$$

Equation 10 is identical in form to equation 3, which was determined experimentally, thus adding confidence to the hypothesis that "τ" is a direct measure of the adhesive force of the toner to the carrier.

Conclusion

Understanding of the physics of magnetic brush development is complicated by the many competing mechanisms that are at play. This purpose of this work was to concentrate only on the adhesion of the toner to the carrier and to discern the important process parameters that affect toner release. A characteristic time constant, which was determined experimentally, was found to be a good measure of relative toner adhesion. This work also demonstrated that toner charge and agitation rate have a greater effect on toner release than the applied electric field.

Acknowledgments

References

1. E. T. Miskinis, *Proc. Sixth Int'l. Cong. on Non-lmpact Printing,* pp. 101-110 (IS&T, Orlando, FL, 1990).
2. Designed by D. Kamp, Eastman Kodak Co.
3. D. A. Hays, *J. Imaging Tech.,* **15**, 29-38, Feb., 1989.
4. D. A. Hays, *Proc. of The Adhesion Society, Seventeenth Ann. Mtg,* pp. 91-93. (The Adhesion Society, Orlando FL, 1994).
5. F. W. Schmidlin, *IS&T Proc. Eighth Int. Cong. on Nonlmpact Printing,* pp. 25-30, (IS&T, Springfield, VA, 1992).
6. D. K. Donald, J. *Appl. Phys,* **40** (1969), 3013-3019.
7. M. H. Lee and J. Ayala, *J. Imaging Technol.,* **11**, (1985), 279-284.
8. M. H. Lee, T. C. Reiley, and C. I. Dodds, *IS&T Proc. on Non-Impact Printing,* pp. 196-206, (IS&T, Springfield, VA, 1990).
9. D. S. Rimai, M. C. Zaretsky, B. Primerano, and J. F. Laukaitis, To be published.
10. G. E. P. Box and N. R. Draper (1987), *Empirical Model Building and Response Surfaces,* John Wiley and Sons Inc.
11. D. K. Donald and P. K. Watson, *IEEE Trans. on Elec. Dev.,* **19**, (1972), 458-462.