The Effect of Carrier Surface Morphology on the Triboelectric and Imaging Performance of Insulative Two-Component Xerographic Developers

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Abstract

Xerography is based on the development of latent electrostatic images by triboelectrically-charged toner particles. In a two-component (TCD) developer, the toner particles are triboelectrically charged via energetic mixing with polymer-coated magnetic carrier beads. Since the TCD xerographic development process is non-linearly related to TCD developer properties (e.g. toner charge, toner supply, powder flow mechanics, etc.), TCD aging can be a major factor for eventual imaging failure. In this review, simple parametric models of triboelectric charging and xerographic development will be combined to illustrate some of the major effects of changes in carrier bead surface chemistry on insulative TCD xerographic development.

Theory

Two-component Triboelectrification

For a well-mixed two-component xerographic developer, the toner ***q/m*** can be simply related to toner and carrier charge properties by the following parametric equation:

$$\boldsymbol{q/m} = (A' \cdot (\phi_{toner} - \phi_{carrier})) / (C + C_0) \qquad (1)$$

where C is the toner concentration; C_0 is an offset constant term that is a function of the diameter and density of both the toner particles and the carrier beads; A' is a function of carrier size and density [1,2].

For simple TCD carrier aging, the charging ability of the carrier beads will approach zero at long aging times (i.e., when $\phi_{aged\ carrier} = \phi_{toner}$), and the product $\boldsymbol{q/m}_t \cdot (C_t + C_0) = A_t$ can be used as a measure of carrier aging at intermediate aging times [3].

Insulative TCD Development

In this mode (the so-called insulative magnetic brush, IMB), a mixture of toner particles and carrier beads has a zero net-charge, with equal and opposite charges residing on the toner and carrier particles. During IMB development, charged toner particles are stripped from the carrier beads by the attractive forces of the latent electrostatic image, thereby leaving charged carrier beads in the post-development magnetic brush. As a result, the IMB mode is not efficient, since charged carrier beads effectively create an opposing electrical bias for continued development of toner particles, and can also scavenge developed image toner particles back into the magnetic brush [4-12]. To increase the toner supply available for development from an IMB developer, various strategies have been devised: (a) a tandem array of multiple development brushes [13], so that development involves a series of "fresh" zero-net-charge developers; (b) increased mechanical [14] or magnetic agitation [15] in the development zone, to facilitate toner migration; (c) application of an AC field to the development zone, to stimulate toner agitation [16].

For slow xerographic process conditions, the level of IMB development can approach an ultimate state where the development field between the photoreceptor and the magnetic development brush is totally balanced by the layer of triboelectrically-charged imaged toner particles. In such a case, for constant process conditions, solid area image development is simply related to the image potential V_i, and toner ***q/m*** by:

$$\mathbf{dma} = (\kappa \cdot (V_i - V_{bias})) / \left| \boldsymbol{q/m} \right| \qquad (2)$$

where **dma** is the developed image mass (mg/cm^2), κ is a process/materials-specific constant, and V_{bias} is a d.c. electrical bias applied to the development brush to minimize background (i.e., non-image) development.

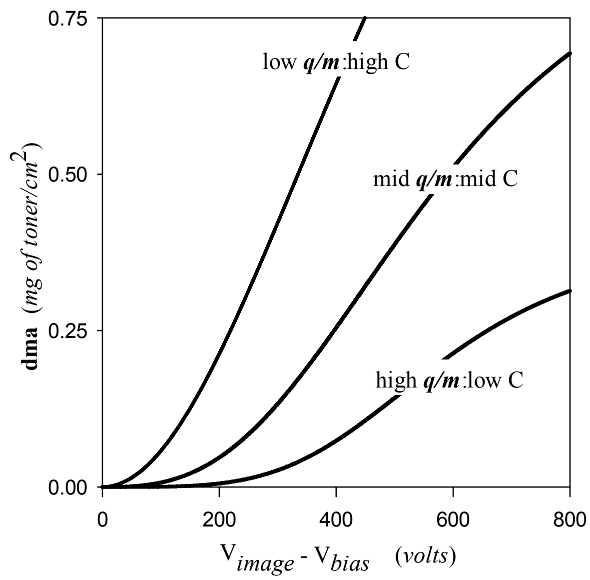

Figure 1: IMB xerographic development as a function of toner ***q/m*** and C.

However, for practical IMB development, **dma** is typically reduced from the maximum value predicted by Eqn. 2, as a result of toner supply limitations. Additionally, **dma** may be affected by an *in-situ* bias as a result of triboelectrification between the photoreceptor surface and the development brush [11,12]. As a result, as shown in Figure 1, IMB development can be constrained by a non-linear **dma** response to (V_{image}-V_{bias}), coupled with a positive threshold development voltage.

To describe xerographic development curves of the type shown in Figure 1, it is convenient to expand Eqn. (2) by including a toner concentration-driven supply constant, δ , and an offset voltage, V_{off} to create a modified parametric descriptor [17]:

$$\mathbf{dma} = \delta \cdot C \cdot (1 - \exp\{(-\kappa \cdot (V_i - V_{bias} - V_{off})) / (\delta \cdot |\boldsymbol{q/m}| \cdot C)\}) \quad (3)$$

Conceptually, the offset voltage V_{off} will be a function of carrier/photoreceptor triboelectric charging at low toner concentrations, and toner/photoreceptor triboelectric charging at high toner concentrations, and V_{off} can be simply related to carrier and toner contributions by:

$$V_{off} = V_{carrier} \cdot (1- \theta) + \theta \cdot V_{toner} \quad (4)$$

where θ is the surface concentration of toner particles on the carrier beads (i.e. $\theta = \gamma \cdot C$), $V_{carrier}$ is the offset voltage generated by detoned carrier beads, and V_{toner} is the offset voltage from a monolayer of toner particles on the carrier beads.

For the case where carrier beads age via an accumulation of impacted toner V_{off} will be given by:

$$V_{off} = V_{carrier} \cdot ((1- \theta) \cdot (exp\{-k \cdot t\})) + V_{toner} \cdot (1-(exp\{-k \cdot t\}) \cdot (1- \theta)) \quad (5)$$

where k is the triboelectric aging rate constant.

Results

Model Prediction for a Simple IMB Developer

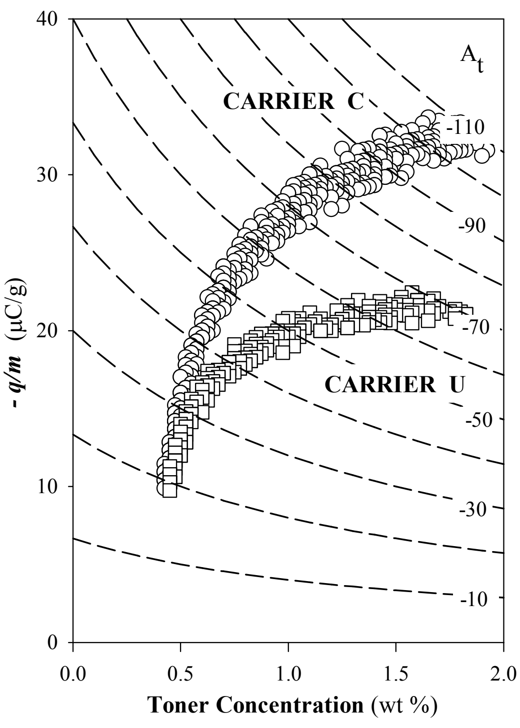

Figure 2: **dma** = 0.5mg/cm^2 isodensity contours for two negative IMB developers.

The isodensity model for carrier C in Figure 2 illustrates the effect of triboelectric aging on solid-area image development for a simple negative polarity IMB developer, based on 130 μ coated ferrite carrier beads and 9 μ Sty/Ac toner particles, with $\delta = 2.5$, $\kappa = 0.09$, **dma** = 0.50 ± 2%, $A_0 = -110$, $C_0 = 1.5$, $k = 0.010$, $\gamma = 0.18$, $V_{carrier} = 148$ volts, $V_{toner} = 268$ volts, $(V_{image} - V_{bias}) = 588 \pm 2\%$.

The isodensity model for carrier U in Figure 1 is for a simple negative polarity IMB developer, based on 130 μ **uncoated** ferrite carrier beads and 9 μ toner particles, with $\delta = 2.5$, $\kappa = 0.09$, **dma** = 0.50 ± 2%, $A_0 = -70$, $C_0 = 1.5$, $k = 0.005$, $\gamma = 0.18$, $V_{carrier} = 350$ volts, $V_{toner} = 268$ volts, $(V_{image} - V_{bias}) = 588 \pm 2\%$.

Model Prediction for a "Small-Carrier" IMB Developer

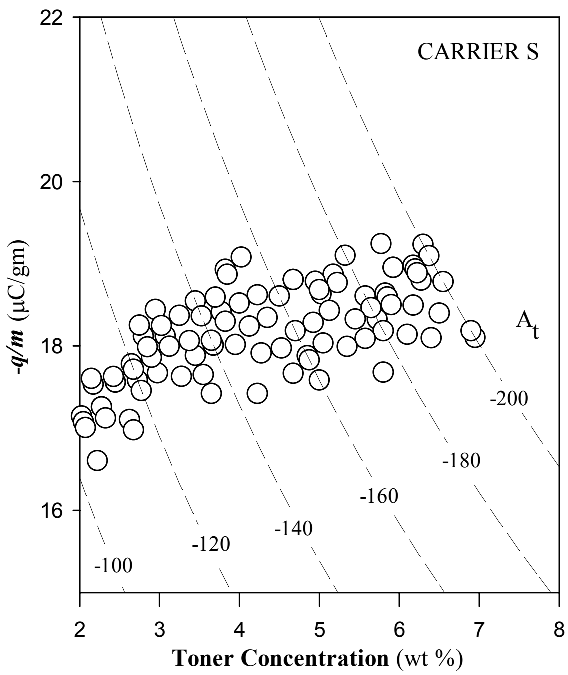

Figure 3: Isodensity contour for an IMB TCD developer based on 35μ ferrite carrier and 6 μ polyester toner.

The present trend towards the use of "small" toner particles in full-color xerographic printers has created a need for IMB TCD developers based on "small" carriers.

Figure 3 shows a model isodensity prediction for a simple IMB TCD developer based on 35 μ coated ferrite carrier beads and 6 μ polyester toner particles, with $\delta = 2.5$, $\kappa = 0.045$, **dma** =0.50 ± 2%, $A_0 = 200$, $C_0 = 4.1$, $k = 0.0025$, $\gamma = 0.067$, $V_{carrier} = 150$ volts, $V_{toner} = 200$ volts, $(V_{image} - V_{bias}) = 588 \pm 2\%$.

With respect to triboelectric charging, the change from a "large" 130μ ferrite-based carrier to a "small" 35μ ferrite-based carrier creates a reduced sensitivity of ***q/m*** to toner concentration.

Xerographically, as shown in Figure 3, the model "small" ferrite-based developer produces a constant level of image development at a constant ***q/m*** value, for all toner concentrations in the 3 to 7 wt% range.

Model Prediction for a Positive CCA-based IMB Developer

While toner CCA's are often used to impart a desired level of toner charge and polarity, CCA-based toners can also generate complex triboelectric aging profiles, and Figure 4 shows a model A_t aging track.

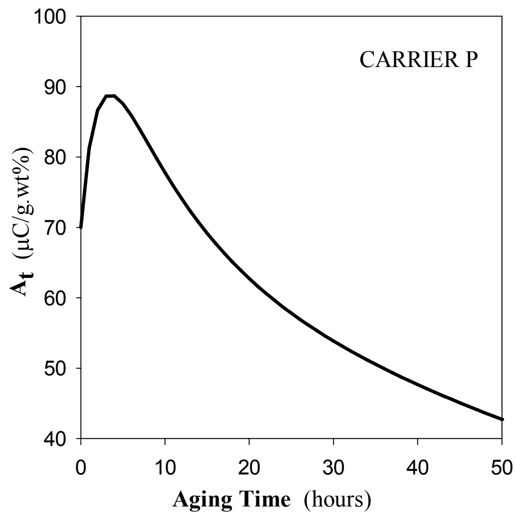

Figure 4: A_t vs. aging time for a positive CCA polarity toner coupled with a coated steel carrier.

For a model 9μ positive CCA toner coupled with a 125μ acrylate-fluoropolymer-coated steel carrier, the triboelectric aging profile has an initial increase in A_t (preferential carrier coating loss; carrier contamination by specific toner components?), followed by a rapid decline (CCA contamination?), along with an underlying steady first-order degradation process (toner impaction?).

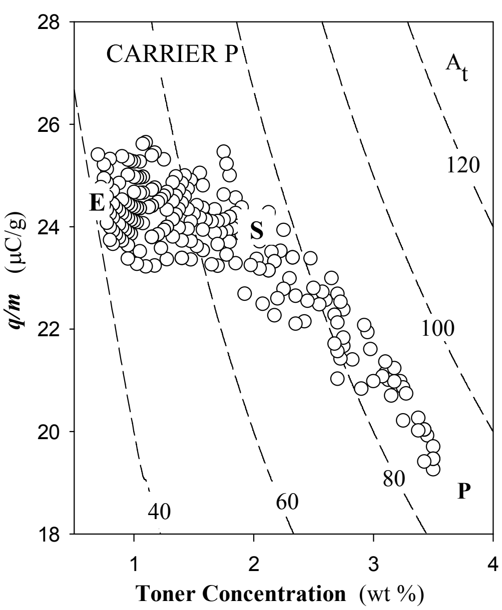

Figure 5: Isodensity contour for a positive CCA toner with a steel IMB carrier. **S** = A_{start}, **P** = A_{peak}, **E** = A_{end}

To model this type of IMB TCD developer, the controlling triboelectric and xerographic factors were set as: $\kappa = 0.14$, **dma** = $0.50 \pm 2\%$, $A_0 = 70$, $C_0 = 1.0$, $k = 0.01$, $\gamma = 0.27$, $A_t = 40 \cdot exp\{-0.1 \cdot t\} + 70 \cdot exp\{-0.01 \cdot t\} - 40 \cdot exp\{-0.5 \cdot t\}$, $V_{toner} = 60$ volts, $V_{carrier} = -10$ volts, $(V_{image} - V_{bias}) = 200$ volts, and development is assumed to follow a simple low-field relationship:

$$\mathbf{dma} = (\kappa \cdot (V_i - V_{bias} - Voff)) \,/\, \boldsymbol{q/m} \qquad (6)$$

The predicted isodensity contour as a function of carrier age is shown in Figure 5, where the initial control point is at **S**, the intermediate (increased A_t) is at point **P**, and the long-term aged point is at **E**. This, then, is an extreme example of the effect of triboelectric aging on xerographic imaging performance.

Summary and Conclusions

The model isodensity contours shown in this report represent just some of the many effects that triboelectric aging can have on xerographic development. Besides the IMB development mode considered in the present study, TCD development can also be based on conductive development [11,12,18], on magnetically-agitated development [15], on AC-stimulated development [16], and on powder-cloud development [19]. While these enhanced development technologies can create a higher level of xerographic development than that of IMB development, they all require complex developer materials designs, and are thereby subject to triboelectric charging failure modes beyond those typical of simple IMB developer designs [20]. For example, a major decrease in ***q/m*** created by an increase in ambient relative humidity (reflecting RH-driven changes in the ϕ_{toner} and $\phi_{carrier}$ values of toner particles and carrier beads based on complex materials designs) can create a significant increase in xerographic image and non-image development. Similarly, toner "aging" (e.g., as generated by an extended development housing residence time during low-area printing) can produce an abrupt decrease in xerographic image development and a step-function increase in non-image development, following an increase in the rate at which toner is dispensed into the working developer. For both RH-driven and toner "aging" processes, the xerographic effect will be a random event independent of any long-term aging process, and will thereby be a complex problem for process control. Similarly, for xerographic development technologies that are affected by several independent developer materials properties (e.g., toner ***q/m*** coupled with developer conductivity, toner cohesion, etc. [12,18,20]), multiple developer aging modes can create conflicting responses to process control and thereby produce irreversible failure modes.

Using actuators such as toner concentration, photoreceptor charge level, applied electrical bias, laser or LED imaging intensity, adaptive xerographic process controls can counteract many triboelectrically-driven changes in xerographic development [21-24]. However, even with complex control algorithms, non-linear imaging/actuator dependencies may introduce additional xerographic imaging failure modes. For example, a controlled decrease in toner concentration may provoke a bead-carryout failure, while a major controlled increase in toner concentration may adversely affect developer flow, increase non-image area development, and increase the level of free-flying toner "dirt". Similarly, while changes in actuators such as toner concentration,

V_{image} (via photoreceptor charging or imaging light intensity) and V_{bias} may all be manipulated to achieve a set high-density image, they can differ in their effect on highlight image densities, and thence on the ability of a xerographic printer to maintain a specific tone reproduction response.

Accordingly, continued improvements in the stability of xerographic development will require the collaborative efforts of materials scientists, xerographic engineers, and process control software engineers. To facilitate such efforts, materials scientists should broaden their knowledge of the physics of xerographic development, xerographic engineers should increase their understanding of materials chemistry, and control engineers should continue to develop control algorithms based on total system integration concepts.

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Biography

Robert Nash received his Ph.D. in Physical Chemistry from the University of Bristol, England. He joined the Xerox Corporation in 1970. From 1998 until the end of 2000 he was an expatriate at Fuji Xerox, Takematsu, Japan. He now consults on topics from xerographic materials to cross-cultural interactions with Japan. In 1999, he was named as a Fellow of the IS&T, and in 2002 he received, jointly with John Bickmore, IS&T's Chester Carlson Award.