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Modeling and Control of Toner Material State in Two Component Development Systems

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Abstract. *Xerographic toners are typically blended with additives for adhesion control in development and transfer processes. Surface additives, 10–100 nm in size, are used to space toners away from the electrode surfaces, thereby lowering adhesion forces. However, in a developer housing, additives get buried into the toner over time due to the repeated mechanical stresses encountered. This is referred to as toner aging. Aged toners can have significantly higher adhesion forces and often perform poorly in development and transfer. In this article, we will discuss models for estimating the surface additive coverage distribution on toners in the developer housing and its impact on development and transfer performance. The use of models to evaluate options for the control of the toner material state will be discussed.* © *2009 Society for Imaging Science and Technology.*
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INTRODUCTION

In electrophotography, charged toner particles are moved from one surface to another by applying electrostatic fields, whereby the resulting electrostatic forces on the toners are used to overcome the surface adhesion forces. For instance, during the development process, toners are moved from the carrier surface to the photoconductor surface, and during the transfer process the toners are moved from the photoconductor surface to the paper surface. Control of adhesion of toner particles is critical to achieving a stable image quality in the electrophotographic process. To this end, nm-size additives are added to the toners. These additives, typically 10–100 nm silica particles, adhere preferentially to edges and holes on the toner surfaces.[1] The effect of the silica additives on toner adhesion has been studied extensively in the past. Iimura et al.[2] showed experimentally using a centrifuge that the adhesion forces of tribocharged toners decrease exponentially with increasing surface additive coverage. They used the charge patch model to propose that increasing the surface additive coverage on toners increases the total charged area on the toner particles, resulting in a more uniformly charged toner. Gady el. al.[3] showed a rapid decrease in the applied voltage required to achieve 90% transfer efficiency with increasing silica content in toners. They suggest that additives might act as asperities that prevent intimate contact between surfaces.

In a typical two component development housing (see, for example, Schein[4]), toners and carriers are mixed in the sump at a specified ratio known as the toner concentration (TC). This mixture is picked up by a developer roll, metered using a trim bar to achieve a uniform thickness, and transported to the development zone where the toners are presented to the image on the photoconductor. Toner and carrier particles are repeatedly subject mechanical stresses during the mixing, trimming, and development processes. Computer simulations have been used to study the motion of carrier particles around the developer roll (see, for example, Kawamoto[5]). Simulations suggest that regions of highest stress in the housing are at the trim bar. The amount of stress on the developer material depends on the strength of the trim pole magnets, the speed of the developer roll, and the trim bar gap.

The loss in functionality of developer material due to the repeated mechanical stresses over time is referred to as aging. The decline of developer conductivity with age of the developer and its impact on the development performance for conductive magnetic brush systems was studied by Nash et al.[6] Another aspect of developer aging is toner impaction on carrier surfaces which affects the tribocharging characteristics of the toner.[7] Trickle[8] has been used to extend the developer life by adding small amounts of fresh carrier with the toner dispense. In all of the above mentioned studies, the focus of aging is the state of the carrier surface over time. However, the effect of the mechanical stresses on the toner surfaces may be equally important. We refer to this as toner aging. Figure 1 shows photomicrographs of two toner particles: one fresh and the other aged for 60 min in a developer housing. The fresh toner has significant surface additive coverage, whereas the aged toner has almost no additives on the surface. Chemical analysis reveals that the additives are buried beneath the surface in the aged toner. Due to the significant dependence of the adhesion forces on the surface additive coverage as discussed previously, one would expect fresh toners and aged toners to perform differently during development and transfer, and this has been observed experimentally.

The surface additive coverage on the toners in a development housing is a distribution that depends on the area coverage of the images that have been run through it. For

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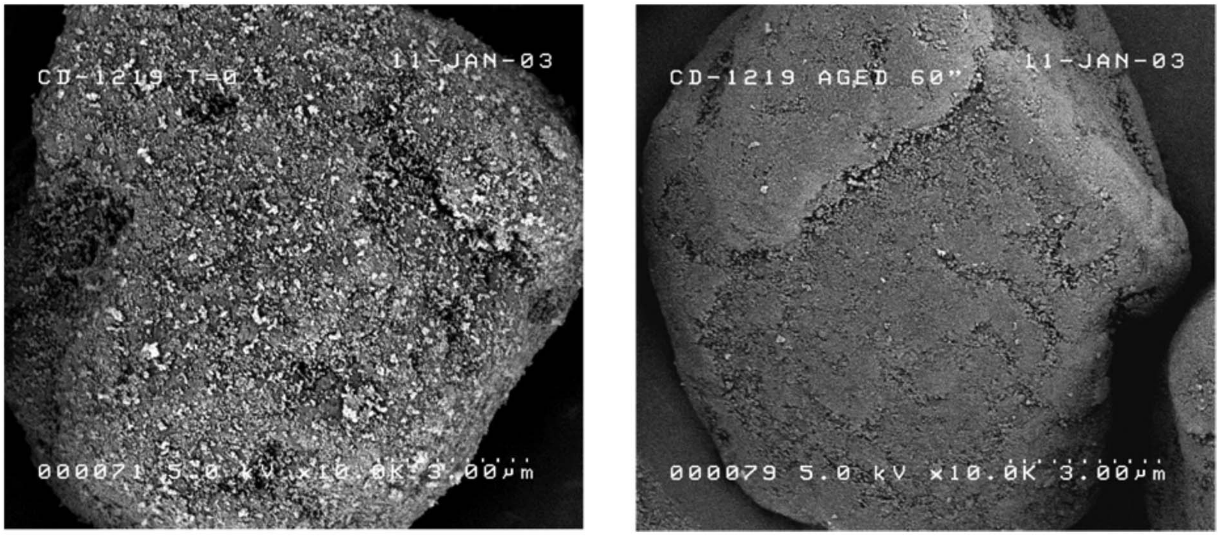

Figure 1. Photomicrograph for fresh toner on the left and 60 min aged toner on the right.

high area coverage (HAC) print jobs, a significant fraction of toners are likely to be "fresh" and have a high surface additive coverage. Conversely, for low area coverage (LAC) print jobs, a significant fraction of toners are likely to be "aged" and have a low surface additive coverage. In general, the toners in the developer sump will have a distribution of surface additive coverage, and the development and transfer performances will depend on this distribution. In this article, we will discuss how the distribution of surface additive coverage on toners can be modeled. This distribution can be used to obtain the average surface additive state of the toners in the developer sump which can be related to the development and transfer performance.

MODELING THE SURFACE ADDITIVE STATE OF TONERS

Figure 2 shows a schematic of mass balance in a developer housing: M_s is the sump developer mass; M_t is the sump toner mass $=M_s\mathrm{TC}/(1+\mathrm{TC})$, where TC is the toner concentration in the sump defined as M_t/M_c; M_c is the sump carrier mass $=(M_s\text{-}M_t)$; D_t is the replenisher dispense rate, and C_t is the toner throughput rate; R_w is the trickle waste; TC_0 is the toner concentration in the replenisher.

The toner mass balance (neglecting toner emissions and bead carry out, etc.) may be written as

$$M_t(t+dt) = M_t(t) + \left(D_t \frac{\mathrm{TC}_0}{1+\mathrm{TC}_0} - C_t - R_w \frac{\mathrm{TC}}{1+\mathrm{TC}} \right) dt. \tag{1}$$

Let $g_s(\tau,t)$ be the age distribution of toners in the sump, i.e., the fraction of toners with residence time τ at time t. Thus,

$$\sum_{\tau=0}^{t} g_s(\tau,t) = 1, \;\; g_s(\tau,t) = 0 \quad \text{for} \;\; \tau > t. \tag{2}$$

We assume that at $t=0$ the toners are fresh, i.e., $g_s(0,0)=1$.

The evolution of the age distribution can be written as

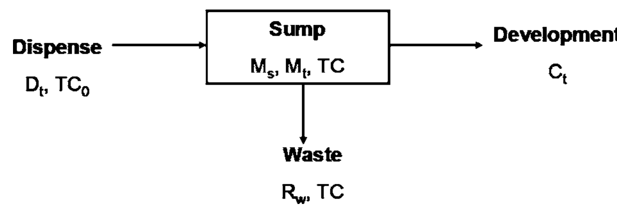

Figure 2. Schematic of mass balance in a developer housing.

$$M_t(t+dt) g_s(\tau+dt, t+dt) = \left(M_t(t) - R_w \frac{\mathrm{TC}}{1+\mathrm{TC}} dt \right) g_s(\tau,t) - C_t g_d(\tau,t) dt,$$

$$M_t(t+dt) g_s(0, t+dt) = D_t \frac{\mathrm{TC}_0}{1+\mathrm{TC}_0} dt. \tag{3}$$

Here g_d is the age distribution of the developed toners on the photoconductor.

Next we consider the surface additive state on the toners. Let $N_f(\tau,t)$ represent the number of additives on a toner of age τ at time t. A normalized value of $N_f=1$ represents the number of additives on toners in fresh developer. Let $g_{sa}(\tau_1,\tau,t)$ be the fraction of additives ($N_f(\tau,t)$) that have been resident on the toner for time τ_1 ($\tau_1 \le \tau$). Thus $\Sigma_{\tau_1} g_{sa}(\tau_1,\tau,t)=1$. Also, let p_a be the fraction of free additives in dispense. For simplicity, we assume that these free additives are instantly blended and uniformly distributed among the developer surfaces in the sump (both carrier and toner). Then we may write the evolution of the surface additive state as follows:

$$N_f(\tau+dt, t+dt) = N_f(\tau,t) + p_0,$$

$$g_{sa}(\tau_1+dt, \tau+dt, t+dt) = \frac{N_f(\tau,t)}{N_f(\tau+dt, t+dt)} g_{sa}(\tau_1,\tau,t),$$

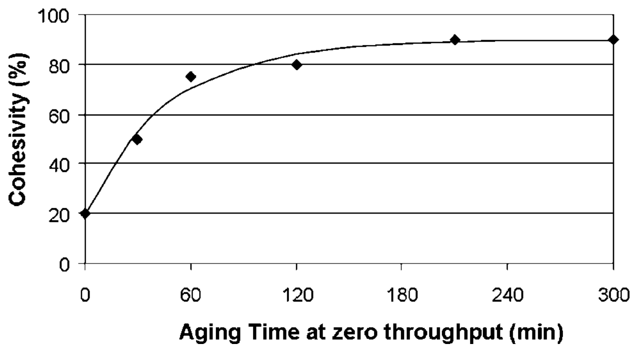

Figure 3. Toner cohesivity vs age.

$$g_{sa}(0,\tau+dt,t+dt)=\frac{p_0}{N_f(\tau+dt,t+dt)},$$

$$g_{sa}(0,0,t+dt)=1. \tag{4}$$

Here $p_0=\frac{1}{M_t}p_aD_t\frac{\mathrm{TC}_0}{1+\mathrm{TC}_0}dt\left(1/\left(1+\frac{1}{\mathrm{TC}}\frac{\rho_t}{\rho_c}\frac{d_t}{d_c}\right)\right)$ is the amount of fresh additives added to incumbent toners; d_t and d_c are toner and carrier diameters, respectively; ρ_t and ρ_c are the toner and carrier mass densities, respectively.

Figure 3 shows a typical plot of toner cohesivity with age which can be fit to an exponential. The increase in cohesivity with age is believed caused by a decrease in the surface additive coverage due to additive burial. Let T_b be the exponential time constant for additive burial. Then the surface additive state of a toner with residence time τ at time t may be written as

$$P_s(\tau,t)=N_f(\tau,t)\sum_{\tau_1=0}^{\tau}e^{-\tau_1/T_b}g_{sa}(\tau_1,\tau,t). \tag{5}$$

After some simplification, the evolution of the surface additive state of the toner $P_s(\tau,t)$ may be written as

$$P_s(\tau+dt,t+dt)=p_0+e^{-dt/T_b}P_s(\tau,t),$$

$$P_s(0,t+dt)=(1-p_a)+p_0. \tag{6}$$

The first term above is the effect of free additives from the dispenser and the second term is the effect of additive burial. Finally, we can define the normalized developability (γ_s) as the average surface additive state of the toners in the sump and normalized transferability (γ_d) as the average additive state of the developed toners on the photoconductor,

$$\gamma_s(t)=\sum_{\tau=0}^{t}P_s(\tau,t)g_s(\tau,t),$$

$$\gamma_d(t)=\sum_{\tau=0}^{t}P_s(\tau,t)g_d(\tau,t). \tag{7}$$

One might expect the development and transfer performance to be dependent on γ_s and γ_d, respectively. These in turn depend on the additive burial process and the dispense history which largely depends on the customer image. We can also specify the average age for toners in the sump and the photoconductor as

$$\bar{\tau}_s=\sum_{\tau=0}^{t}\tau g_s(\tau,t),\quad \bar{\tau}_d=\sum_{\tau=0}^{t}\tau g_d(\tau,t). \tag{8}$$

To complete the description of the model given by Eqs. (1)–(8), we need to specify how the age distribution of developed toners $g_d(\tau,t)$ is determined. This depends on the development probability (P_d) of sump toners. Let us consider two cases.

(a) Uniform development probability for all toners ($P_d=1$),

$$g_d(\tau,t)=g_s(\tau,t).$$

(b) Development probability of toners given by their surface additive state ($P_d=P_s$),

$$g_d(\tau\,.\,t)=\frac{1}{\gamma_s(t)}g_s(\tau,t)P_s(\tau,t).$$

Note that cases (a) and (b) are somewhat analogous to the "equilibrium" theory and "field stripping" theory in Schein's discussion of the theories of development.[9]

TONER MATERIAL STATES VERSUS THROUGHPUT

Consider a developer sump with mass $M_s=3500$ gm at a TC=4% (toner mass $M_t\approx 135$ gm). The replenisher toner concentration $\mathrm{TC}_0=200\%$ and fraction of free additives in the replenisher $p_a=0.25$. The additive burial time constant $T_b=45$ min (from Figure 3). We will assume that the sump TC is maintained constant and the excess mass is trickled out. One can identify three regimes of behavior depending on the throughput rate (C_t): (a) LAC where $M_t/C_t \gg T_b$; (b) nominal area coverage (NAC) where $M_t/C_t\approx T_b$; and (c) HAC where $M_t/C_t \ll T_b$. Note that M_t/C_t is a crude estimate of the toner residence time in the sump. For the example here, we will choose $C_t=1$ gm/min, 3 gm/min, and 15 gm/min to represent the LAC, NAC, and HAC regimes, respectively. The simulations are run for 300 min starting with an initial sump of fresh toner, i.e., $g_s(0,0)=1$, $P_s(0,0)=1$. For the example here, we assume that the development probability with age is given by the surface additive state of toners in the sump ($P_d=P_s$).

Figures 4–7 show plots of average age of toners (τ_s,τ_d), sump toner age distribution at 300 min, toner surface additive distribution at 300 min (P_s), and evolution developability (γ_s) and transferability (γ_d) over time, respectively. Age distribution in the sump (Fig. 5) shows significant fraction of aged toners for the LAC case. This is reflected in the high average toner age (Fig. 4). The average toner age on the photoconductor is lower because we assume that toners with higher surface additive coverage (i.e., fresh toners) are preferentially developed. The surface additive state distribution with age (Fig. 6) shows the impact of free additives for the HAC case.

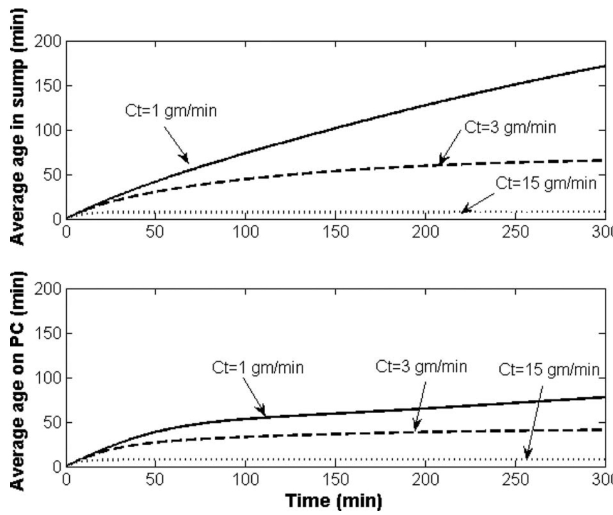

Figure 4. Average toner age in the sump (top) and photoconductor (bottom) for various values of C_t.

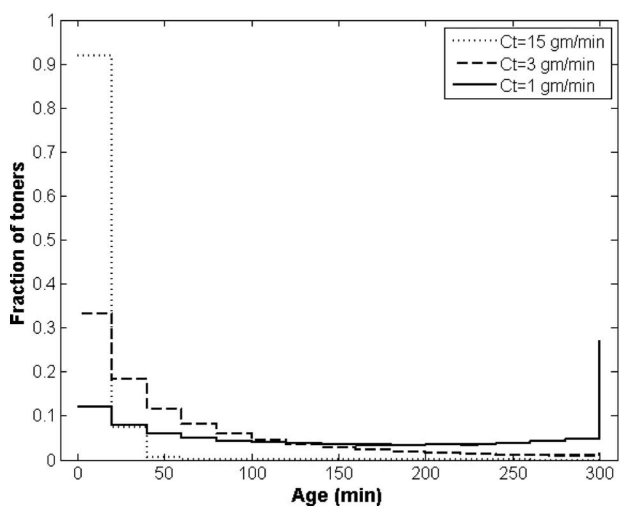

Figure 5. Sump toner age distribution at 300 min.

TONER MATERIAL STATE CONTROL

The toner material state models discussed here provide useful means to evaluate control options to regulate printer performance. The mean residence time of toners in the developer sump is often used as an estimate of the toner material state. However, as is evident from Fig. 5, the toner age distribution is not uniform and the mean residence time is often a poor representation of the distribution. We propose that the normalized developability (γ_s) and transferability (γ_d) as more representative metrics of the toner material state since they comprehend the distribution in age as well as the state of additive impaction. Figure 8 shows a plot of the calculated transferability parameter (γ_d) versus the measured transfer efficiency. The transfer efficiency measurements were made on a printer running low area coverage. Clearly the correlation between transfer efficiency and transferability parameter is good. We have observed similar correlation between the development slope and developability parameter (γ_s).

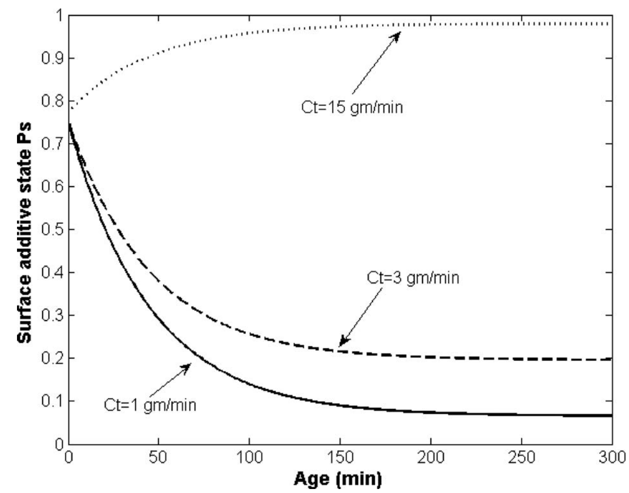

Figure 6. Surface additive state distribution at 300 min.

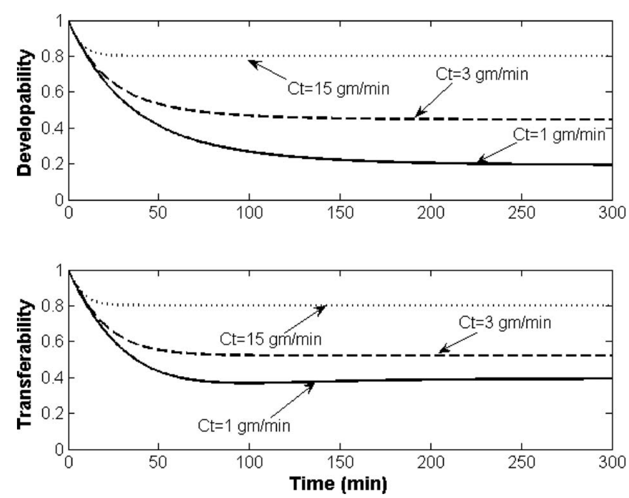

Figure 7. Evolution of normalized surface additive states for toners in the sump (top) and photoconductor (bottom).

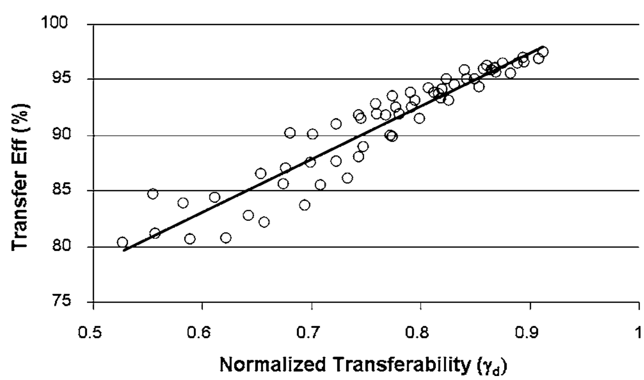

Figure 8. Transfer efficiency versus transferability (γ_d).

In order to maintain print quality, it is desirable to maintain the transfer efficiency above a threshold value. Let us consider the control scheme shown in Figure 9, where the transfer efficiency is estimated and controlled by regulating the toner dispense. Additional details were discussed by Ramesh et al.[10] The toner dispense is regulated by adjusting the toner concentration (TC) target. However, the toner concentration must be maintained within bounds in order

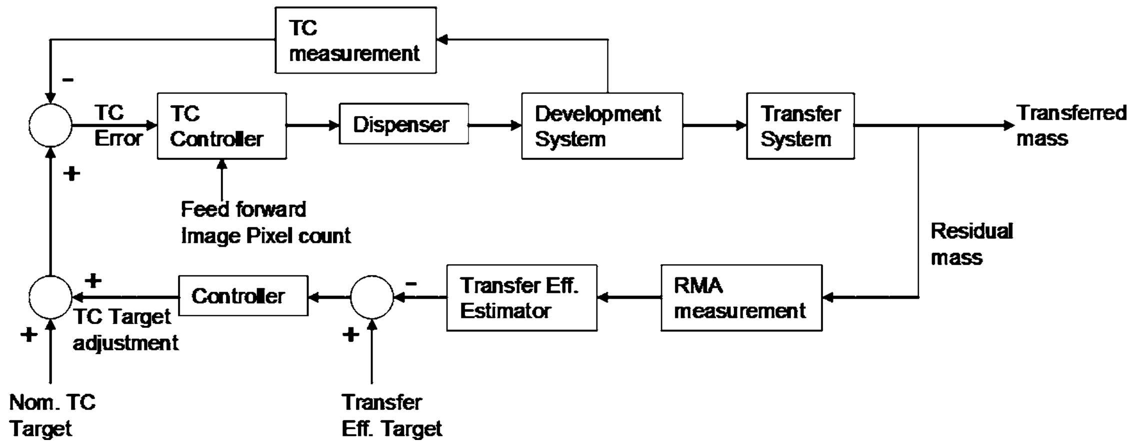

Figure 9. Example of transfer control through dispense regulation.

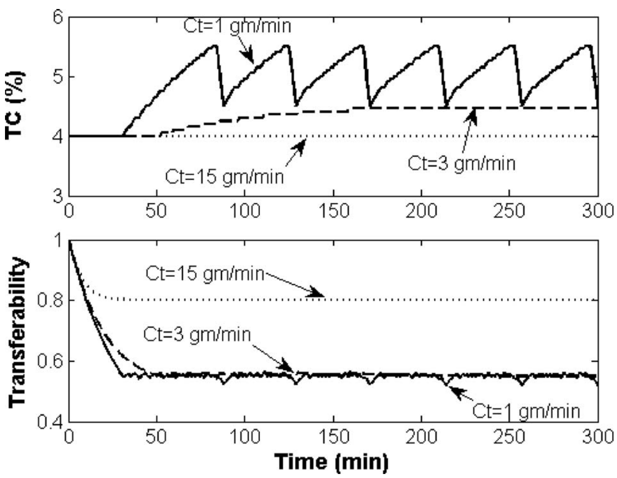

Figure 10. Simulation of transfer control using dispense regulation.

to stay away from failure modes such as bead carry out (at low TC) and emissions and background (at high TC). When the TC reaches the upper bound, a detone procedure is used, where the TC target is reset to a nominal value and additional toner is removed from the developer sump to nonprinting areas of the photoconductor.

Figure 10 shows an example of regulating dispense to maintain transferability at or above 0.55 which corresponds to a transfer efficiency of about 80%. In this example, we have included a scaling factor of 1/tribo to the computed transferability to account for the effect of varying TC on transfer efficiency. For the LAC case ($C_t = 1$ gm/min), the transferability threshold is reached at about 30 min at which point the TC target is gradually increased from an initial value of 4% in order to maintain the transferability at its threshold value. When TC reaches an upper bound of 5.5%, a detone procedure is used to lower the TC to 4.5%. We observe that a detone procedure is required at an interval of about 40 min. For the NAC case ($C_t = 3$ gm/min), the transferability threshold is reached at about 50 min. At this point, the TC target is gradually increased from an initial value of 4% to a final value of 4.5%, in order to maintain the transferability at its threshold value. No detone is necessary because the TC is lower than the upper bound. Finally, for the HAC case ($C_t = 15$ gm/min), no TC adjustment is required since the transferability is always above the threshold value. A more comprehensive approach to toner material state control based on the model predictive control framework was discussed by Gross and Ramesh,[11] where dispense and toner throughput rates are actuated to simultaneously manage TC and toner age.

CONCLUSION

In this article, we discussed how the distribution of additive burial states on toner surfaces can be modeled. These distributions define the average surface additive state of toners which can be related to the toner adhesion properties and therefore to the development and transfer performance. The models can be used to understand how image quality might be impacted by various customer jobs. These models may also be used to develop control frameworks to maintain image quality.

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