The Effect of Toner and Carrier Physical Properties on Developer Conductivity

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Abstract

The electrical conductivity of a two component conductive developer decreases with increasing toner concentration, since the insulative toner particles block carrier-to-carrier contacts. This effect is a function of toner and carrier physical properties such as size, density and the intrinsic conductivity of the carrier particles. However, this effect can be moderated through additional factors such as carrier surface roughness and lubricating toner external additives. In the present paper, these various effects will be illustrated, using an analysis of experimental conductivity data taken on three sizes of model toners.

Introduction

In a conductive magnetic brush (CMB) developer, the conductive carrier particles provide electrically conductive pathways through the brush. As a result, the development field is confined to the tips of the carrier chains, and toner particles in this region are therefore efficiently driven to the latent electrostatic image.[1,2] The CMB mode of development, therefore, is well suited for development applications that require a high level of development.

However, while conductive carrier particles are a necessary component of a CMB developer, other developer components can strongly affect the overall conductive performance. For example, since toner particles are insulative, the conductivity of a toned CMB developer will always be lower than that of the conductive carrier particles. For many CMB developers, the developer conductivity, •C, at any toner concentration, *C*, can be related to the untoned carrier conductivity, σ_o, by:

$$\sigma_C = \sigma_o.\exp\{-\alpha_C\} \qquad (1)$$

where the α factor is a measure of the sensitivity of σ_C to the toner concentration, and this factor can be related to carrier and toner physical properties such as size, shape, density and surface chemistry.[3,4]

To minimize the sensitivity of developer conductivity to toner concentration, the α factor must be small. This is especially important as a function of developer age, where toner impaction onto the surface of the carrier beads may produce only a minor change in s_o but a major change in the α term.[5,6]

In this present report, experimental data on the effect of toner and carrier physical properties on α will be presented, with especial reference to toner size, carrier roughness and external toner additives.

Experimental

(a) Materials

Carrier: A nominal 100 micron diameter steel grit core, solution-coated with a PMMA/conductive carbon black lacquer.

Toner: A single model toner design at three sizes — 13, 9 and 7 micron volume median diameters, at a 5 micron cutpoint. These base toners were also examined after the combined addition of 0.3 wt% of R972 fumed silica and 0.3 wt% of zinc stearate as external additives. Toner concentrations were prepared from 0.5 to 4 wt %.

(b) Test Procedures

Triboelectric Charge: The toner charge to mass ratio, ***q/m***, and the toner concentration ,*C*, values were measured using a total blow-off Faraday cage.

Developer Conductivity: A miniature magnetic roll assembly was used to create a trimmed magnetic brush from the developer samples,[3,4,7] with a gap of 2.54 mm between the roll surface and a guarded current measurement electrode (3 cm2 in area, 0.5cm wide by 6 cm long). At an applied potential of 10 volts, d.c. to the developer roll, the conduction current ,*I*, was measured with an electrometer connected to the guarded electrode, yielding conductivity values σ defined as:

$$\sigma = (I/10)\cdot(0.254/3)\ (\text{ohm.cm})^{-1} \qquad (2)$$

Carrier Packed Density: Electrical conduction through a magnetic brush involves many carrier-to-carrier contacts along the bristles formed by the carrier beads, so that the conduction process will be strongly influenced by the physical state of the brush. For conductivity, external controlling factors include the strength of the applied magnetic field[8] and the degree of brush compaction ("trimming"), and (for a fixed brush configuration) these affect the packed density of the carrier beads in the brush.[9] Unfortunately, it is difficult to make an accurate measurement of packed density directly from a magnetic brush , so an indirect surrogate test was used for the present tests. Density measurements on untoned carrier beads in a uniform magnetic field have been reported,[9] but for the present study packed density measurements were made using a conventional tapped density procedure[2,10-12] on samples held in a cylindrical volume cell.

Since the conduction through a magnetic brush proceeds through the chained carrier beads, then conduction will be related to the packed density of the carrier beads in the developer rather than to the packed density of the developer itself. Therefore, measurements of the latter density must be converted to an effective carrier density as follows:

$$\rho_{carrier} = M_{carrier}/V \tag{3}$$

i.e.,

$$\rho_{carrier} = (M_{developer}/V) \div (1 + C/100) \tag{4}$$

where $\rho_{carrier}$ is the tapped density of the carrier beads in the toned state, $M_{carrier}$ is the mass of carrier in the mass of developer $M_{developer}$ that fills a calibrated volume V at a toner concentration of C wt %. From $\rho_{carrier}$, the carrier packing fraction $\boldsymbol{f}$ can be calculated using:

$$\boldsymbol{f} = \rho_{carrier}/\rho_{bulk} \tag{5}$$

where ρ_{bulk} is the mass density of the carrier beads as measured by liquid displacement, using isopropyl alcohol (ρ_{bulk} = 7.55 g/cc, and $\rho_{carrier}$ = 3.60g/cc for the untoned test carrier beads).

Results and Discussion

Figures 1 and 2, the developer conductivity vs. toner concentration data for the base and external additive toners, respectively, show that the developer conductivity:toner concentration response increases as toner size decreases, with the base toner developers showing the largest response.

The carrier packed density data vs. toner concentration, Figures 3 and 4, show a similar base toner to additive toner response, but in contrast to the conductivity data, the density response is lowest for the "small toner/external additive" sample.

If toner particles merely sit in the spaces between carrier particles, then the carrier packed density will remain constant over a range of toner concentration, and a conductive developer based on a stearated toner and a smooth, round ferrite carrier is an example of a developer that approaches this limiting condition.[3,13] However, in general, triboelectrically-charged toner particles will be distributed over the entire carrier surface and will thus act as insulative spacers between the carrier particles. For such a case, the effect of toner particles on a carrier packing fraction, $\boldsymbol{f}_C$, at any toner concentration, C, will follow a relationship of the form[14]

$$\boldsymbol{f}_C = (\boldsymbol{f}_o - \boldsymbol{f}_{mono}).\exp\{-k.C\} + \boldsymbol{f}_{mono} \tag{6}$$

where $\boldsymbol{f}_o$ and $\boldsymbol{f}_{mono}$ are the respective carrier density values for untoned carrier and carrier coated with a monolayer of toner particles. For the present toner/carrier combinations, all of the packing density data follow the form of Equation (6), with a predicted limiting reduction in packing density of 15-20% (compared with model limits[14] of 20-30%). At any fixed toner size, a noteworthy difference between the base and additive toner data is in the $\boldsymbol{f}_o$ value — in the presence of the additive toners, the un-toned carrier packed density is increased by 2%.

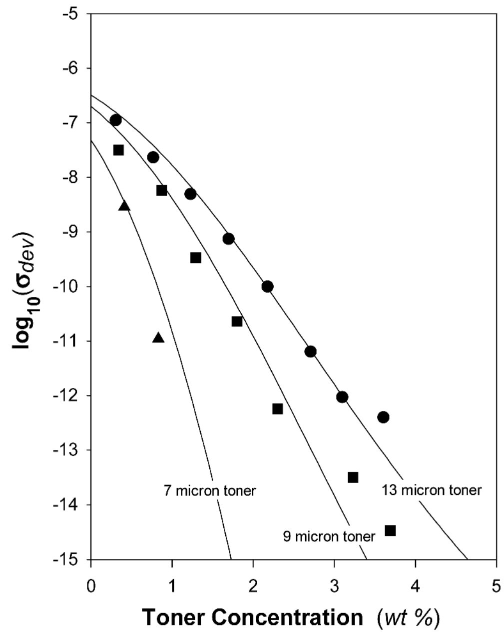

Figure 1. Developer conductivity vs. toner concentration for 7,9 and 13 micron additive-free base toners with 100 micron carrier.

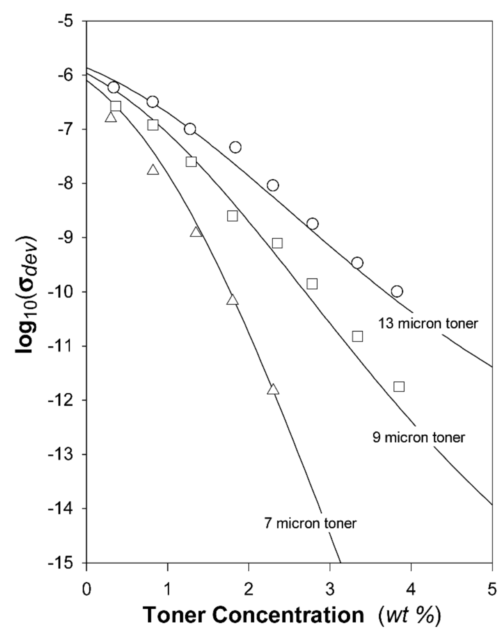

Figure 2. Developer conductivity vs. toner concentration for 7,9 and 13 micron additive toners with 100 micron carrier.

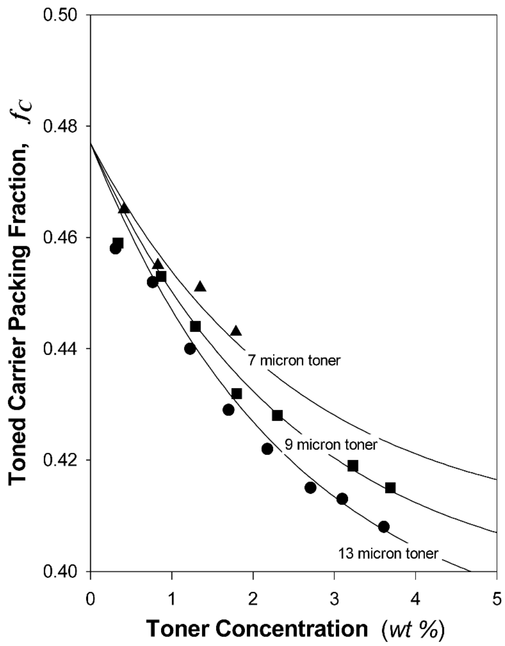

Figure 3. Toned carrier packing fraction vs. toner concentration for 7,9 and 13 micron additive-free base toners with 100 micron carrier.

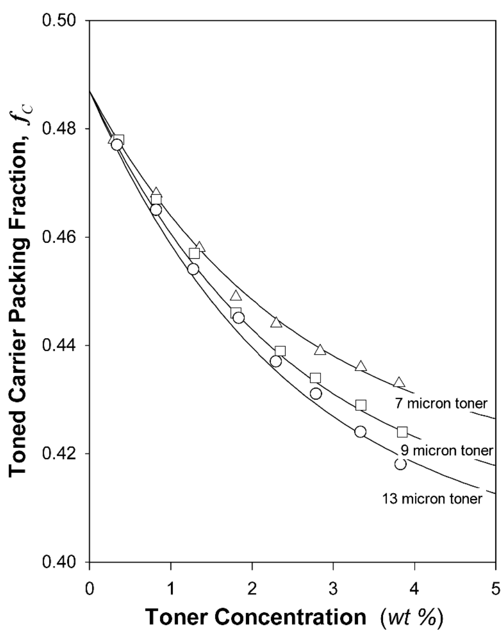

Figure 4. Toned carrier packing fraction vs. toner concentration for 7,9 and 13 micron additive toners with 100 micron carrier.

Since electrical conduction through a toned two component developer follows a percolation pathway between contacting carrier beads, the developer conductivity will be a function of processes that affect the probability for carrier-to-carrier contacts. For fixed brush conditions (e.g., fixed magnetic field, fixed degree of brush compression), Figures 1 and 2 indicate that the concentration of toner particles in the developer is an important conductivity lim-iting factor. For the present test materials, developer conductivity should be related to the carrier packing densi-ty (in the presence of toner particles), since Figures 3 and 4 indicate that toner particles increase the carrier-to-carrier spacing. Indeed, plots of developer conductivity vs. carrier packing fraction, Figures 5 and 6, show a strong relation-ship, and the plots can be described parametrically by:

$$\sigma_C = \sigma_{max}.\exp\{-\mathbf{B}.(\exp\{-\beta.(f_c - f_{ins})\})\} \quad (7)$$

where σ_C is the developer conductivity at a toned carrier packing fraction of f_c, σ_{max} is the limiting, maximum detoned carrier conductivity, $\mathbf{B}$ and β are constants, and f_{ins} is the packing fraction at which the developer becomes totally insulative (with insulative defined as10^{-16} ohm.cm^{-1}, then $\mathbf{B}$ is $\log_e\{\sigma_{max}/10^{-16}\}$).

Equations 6 and 7 can be combined to give a somewhat non-linear equation relating developer conductivity to toner concentration, and the trend lines in Figures 1 and 2 were generated from combinations of the fits to the data in Figures 3-6.

To further explore the toner size effects that are evident in the experimental data of the present study, it is convenient to review the data in terms of the simple relationship given in Equation (1). In this equation, the α term (for toner concentration expressed in wt %) can be related to carrier and toner physical properties by:

$$\alpha = (1/100).(\rho_c\mathbf{R}^3.(\mathbf{r} - \delta))/(\rho_t.\mathbf{r}^3.(\mathbf{R}+\mathbf{r})) \quad (8)$$

where ρ_c and ρ_t are the carrier and toner bulk densities, $\mathbf{R}$ and $\mathbf{r}$ are the carrier and toner radii values and δ is the depth of the roughness depressions on the carrier surface.

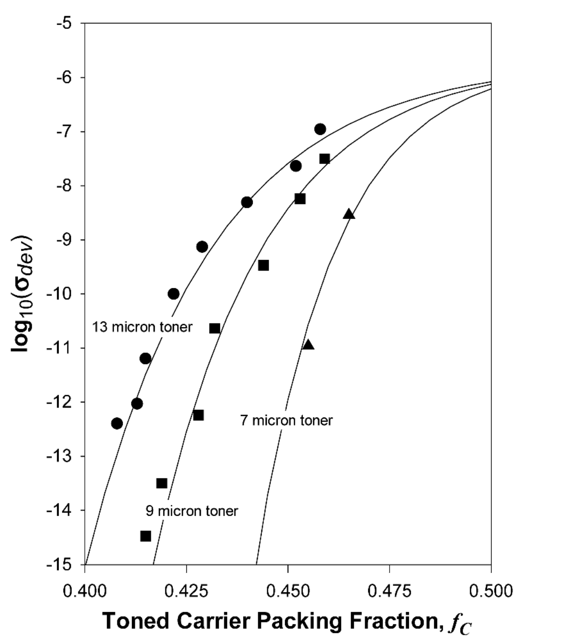

Figure 5. Developer conductivity vs. toned carrier packing fraction for 7,9 and 13 micron additive-free base toners with 100 micron carrier.

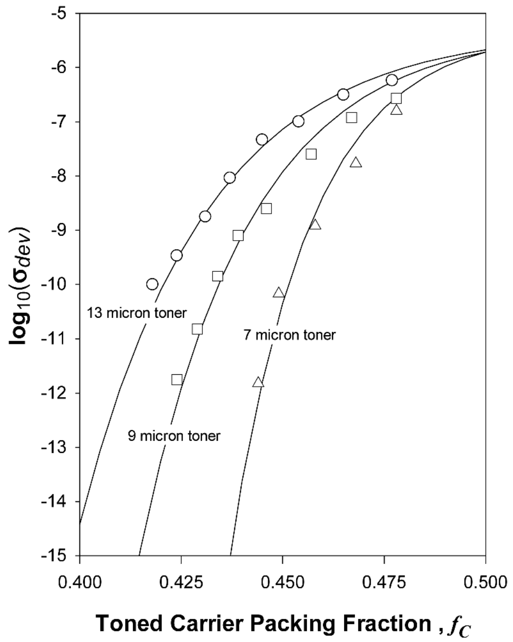

Figure 6. Developer conductivity vs. toned carrier packing fraction for 7,9 and 13 micron additive toners with 100 micron carrier.

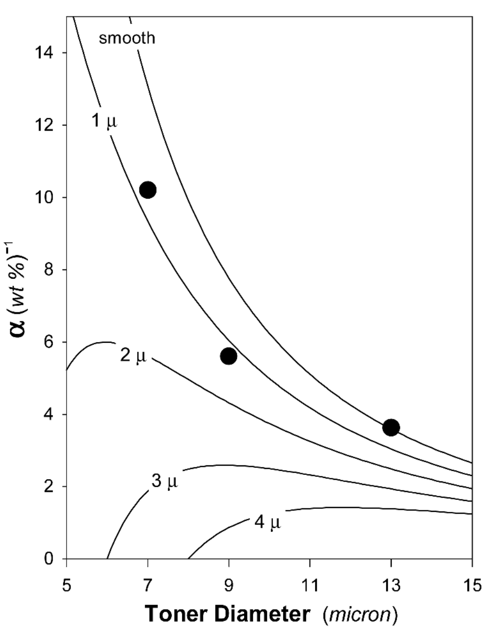

Figure 7. Predicted alpha vs. toner diameter for 100 micron carriers with smooth and rough surfaces (δ = 0 to 4 micron). The data points are from tests on 7,9 and 13 µ additive-free toners.

Figure 7 shows the relationship between α and toner diameter, as predicted from Equation (8) for values of δ from 0 to 4 micron , based on ρ_c =7.55 g/cc , ρ_t = 1.10 g/cc and **R** = 50 micron. The data points in Figure 7 are from the additive-free base toner tests, and a comparison with the model predictions indicates a δ value of about 1 micron for the test carrier.

Figure 8 shows the experimental α:*C* data and predictions for the external additive test toners paired with the same carrier as examined in Figure 7. In Figure 8, it was necessary to scale the predicted α values by a factor of 0.57 in order to match the predicted and experimental α values for a δ value of 1 micron. Since α is a measure of the ability of toner particles to block carrier-to-carrier contacts, it appears (from the reduction factor of 0.57) that the relationship between toner concentration and contact blocking is reduced for the case of the stearated test toners. Apparently, lubrication between the carrier surface and the stearated toner facilitates the movement of the toner particles away from the critical carrier-to-carrier contact zones, thus producing a denser (and more conductive) carrier matrix. (This lubricating effect is not simply limited to the toner particles — after contact with a stearated toner, carrier beads acquire a stearate film15, and this produces an increased packed density for the carrier beads, even after all of the toner has been removed).

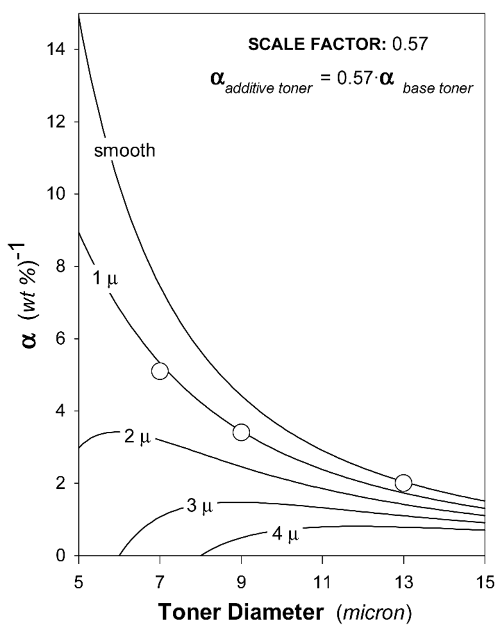

Figure 8. Predicted alpha vs. toner diameter for 100 micron carriers with smooth and rough surfaces (δ = 0 to 4 micron). The data points are from tests on 7,9 and 13 µ additive toners.

With respect to toner size effects, Figures 3 and 4 show that small toner also promotes a denser carrier matrix, but this effect is offset by a higher value for the carrier packing fraction at which the developer becomes insulative (the ***fins*** term) — see Figures 5 and 6. As toner size decreases, the conductive-to-insulative transition will occur at carrier packing fraction values approaching that of the untoned carrier beads, and the developer conductivity will become extremely sensitive to small changes in the carrier packing fraction.

Conclusions

To reduce the sensitivity of developer conductivity to toner concentration, Equation (8) indicates that toner size and carrier surface roughness should be maximized, and that carrier size should be minimized. A reduction in carrier bulk density (e.g., from steel to ferrite) and an increase in toner density are also predicted to be effective for the reduction in α. However, while toner density can be readily increased by the addition of magnetite, this will not reduce α — for the magnetite case, the magnetic toner particles will accumulate in regions of maximum magnetic field flux, and since such regions will be concentrated at the carrier-to-carrier contact points, the overall effect will be an undesirable increase in α.

Finally, the addition of lubricating external additives such as zinc stearate to a two component developer can reduce the sensitivity of developer conductivity to other toner and carrier properties (such as density, size, etc.) by promoting carrier packing and hence carrier-to-carrier contacts. Since Equation[8] predicts that α will be an inverse function of toner size cubed, a combination of increased carrier roughness, reduced carrier size and density plus stearated toners will be necessary to produce low values of α for developers based on small toners.

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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 2002 he served an expatriate assignment at Fuji Xerox, Takematsu, Japan, as the Senior Manager, Resident for the Xerox Supplies Development, Manufacturing and Supply Chain Operations organization. He retired from Xerox in 2002, and currently provides a consulting service on a variety of subjects, ranging from xerographic materials to cross-cultural interactions with Japan. In this way, he hopes to remain abreast of two fascinatingly complex and mysterious subjects: triboelectrification and the Japanese language. His research and modeling studies at Xerox were focused on the design and evaluation of xerographic toners, carriers and developers, with especial emphasis on "aging" mechanisms. Starting with the 4th International NIP Congress in 1988, he yearly presented the results of his studies at the IS&T NIP Conference. In 1990, he served as Publication Chairman for the 6th. NIP Congress, and in 1992 he was Chairman of the IS&T Honors & Awards Committee. 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.