Toner Transfer: Effects of Size Polydispersity

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Toned images comprised of monodisperse, spherical toner particles, having diameters of either 2 μm or 5 μm or of blends thereof were electrostatically transferred from an organic photoreceptor to either paper or film receivers. It was found that the transfer efficiency of the images made with the monodisperse toners was quite high and the image quality quite good. However, even small amounts of the 5 μm toner significantly impeded the transfer of the 2 μm, resulting in much poorer transfer efficiency and a large increase in mottle and granularity. Mathematical analysis shows that the maximum electrostatic field that can be applied prior to the onset of ionization is too small to remove the toner particles from the photoreceptor. Rather, the adhesive forces holding the toner to the photoreceptor must be partially offset by comparable adhesive forces between the toner particles and the receiver for transfer to occur.

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Introduction

In the modern world of digital imaging, the quality of electrophotographic prints is of major concern. Indeed, electrophotographic imaging has, in recent years, gone from a technology mostly suited for making black and white alpha-numeric copies of documents to one capable of producing full-color prints that in which the image quality rivals that produced by silver halide photography and off-set graphic arts printing. The quest for higher image quality has directly led to the use of smaller toner particles. Associated with the use of such toner is an increased difficulty in the electrostatic transfer of toned images from the photoreceptor to the receiver. Unless otherwise specified, the term "toner transfer", as used in this article, will refer to the transfer of toner under the influence of an applied electrostatic field.

Toner transfer has been associated with numerous image defects such as "hollow character" (the failure to transfer the centers of fine lines),[1] "halo" (the failure to transfer toner adjacent to a high density region), "satellites" (the disruption of an image caused by the scattering of toner particles around the actual toned area),[2] etc. In addition, other image quality defects such as increases in mottle and granularity have been associated with poor transfer efficiency. Finally, transferring to materials with irregularly-shaped surfaces, such as textiles and certain graphic arts papers, has presented numerous challenges.[3]

Both the ability to transfer toned images effectively and the propensity to induce image-quality artifacts as a result of the transfer process arise from the forces that act on the toner particles. A detailed discussion of the forces between the toner particles and the photoreceptor and receiver can be found in detail in Ref. [3]. These are, in brief, the electrostatic force between the toner particle and the photoreceptor resulting from the charge on the particle inducing an image charge in the photoreceptor, a van der Waals interaction between the toner particle and the photoreceptor, a van der Waals interaction between the toner particle and the receiver if the toner particle is in contact with the receiver, and the applied electrostatic transfer force. In addition, interparticle forces, while not discussed in Ref. [3], also play an important role. These forces include the electrostatic repulsion between neighboring toner particles and cohesive interactions, presumably resulting from van der Waals interactions, between contacting toner particles.

In recent years, there has been much debate over whether the dominant interaction between toner particles and the photoreceptor arise from van der Waals interactions or electrostatic image forces that are enhanced due to the occurrence of nonuniform charge distributions on the toner particles, often referred to as "charged patches".[4–23] The results of the cited papers are summarized elsewhere.[7] At this point, let us consider the criteria for toner transfer, as predicted assuming that either van der Waals or electrostatic interactions are dominant.

First consider the case where van der Waals interactions dominate over electrostatic forces. If one assumes that the strains in the contacting materials arising from the adhesion-induced stresses are relatively small and elastic, the force F_T needed to transfer toner particles across an air gap is predicted by the JKR theory[24] and is related to the radius R of the toner by

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$$F_T = -\frac{3}{2} w_A \pi R \quad (1)$$

where w_A is the thermodynamic work of adhesion. The minus sign in Eq. (1) indicates that the applied transfer force is in the opposite direction to those forces adhering the toner particle to the photoreceptor. It should be noted that, while the JKR theory allows for work needed to overcome the adhesion-induced deformations of the materials, it is a contact mechanics based theory and, therefore, does not include long-range interactions. It should be noted that the transfer forces estimated by assuming van der Waals interactions are generally in good agreement with the measured forces.[22]

Now consider the case where toner adhesion is dominated by electrostatic forces. It is generally acknowledged that the measured detachment force of toner particles from photoreceptors is much too large to be simply accounted for if the charge on the toner particles was uniformly distributed.[22] This is addressed by assuming that the charge on a toner particle, rather than being uniformly distributed over the entire surface of that particle, is localized to certain high spots. This is referred to as the "charged patch model".[18] According to the charged patch model, toner transfer occurs when the applied transfer force F_T' is equal to the electrostatic attractive force, or

$$F_T' = \frac{\sigma^2 A_C}{2 \varepsilon_0} \quad (2)$$

where σ represents the surface charge density in the vicinity of the contact area A_C and ε_0 is the permittivity of free space. The charged patch model does not take into account any stress related deformations of the toner or photoreceptor.

An issue with which the proponents of the charged patch model had to deal is why van der Waals interactions did not account for the toner adhesion, even though models based on those interactions predicted the correct magnitude of the transfer forces. This was done by arguing that the van der Waals forces are short range, typically on the order of Angstoms.[25] Therefore, the irregular surface of the toner particles would preclude such interactions from becoming significant. In effect, that argument, if correct, would preclude van der Waals forces from being significant for all materials except those that have atomically smooth surfaces, such as mica.

In a recent paper[3] Rimai and Quesnel proposed that toner transfer generally does not occur across an air gap. Rather, transfer occurs when the receiver contacts the toner particles, thereby at least partially offsetting the surface forces between the toner particles and photoreceptor. The role of the applied electrostatic force, then, is simply to exert sufficient force to drive the toner particles to the receiver, much the same way that elevators are counterbalanced and the motor merely exerts a sufficient force to offset the difference in weight between the counterbalancing mass and the elevator. In that paper, they also suggest that toner size polydispersity can create air gaps that impede the transfer of the smaller toner particles.

The results of a study of the effects of toner size polydispersity on transfer are presented in this article. In addition, calculations of the size of the applied electrostatic transfer field are also presented. These results confirm that transferring small toner particles across air gaps can be quite problematical and support the previously reported hypothesis that toner transfer generally occurs when the receiver contacts the toner particle, thereby partially or totally offsetting the surface forces between the toner particles and the photoreceptor.

Experiment

Images made with spherical, monodisperse toner particles having diameters of approximately 2 μm or 5 μm were made on the surface of an organic photoreceptor and electrostatically transferred to either high quality, clay coated graphic arts or photographic papers, or to a film-based receiver. In addition, similar images were made using blends of the 2 and 5 μm toners and transferred to the same receivers. Parameters including transfer efficiency and granularity were determined for the transferred images.

Polystyrene toner particles, containing Sudan Black dye and having a mass density of 1.0 g/cm^3 and diameters of either 2 μm or 5 μm, were produced using a modification of the technique of Vanderhof et al.[26] It should be noted that these particles, being highly crosslinked, cannot be fused. The toner particles and photoreceptor used in this study were the same as those used previously to determine the toner-to-photoreceptor detachment forces.[7] Scanning electron micrographs (SEM) of the toner particles are also shown in Ref. [7]. These micrographs show an absence of any discernible asperities, to within the limits of resolution of the SEM (approximately 10 nm), on the toner particles. Two types of developers were made. In one type, the developer comprised of only one size of toner particle. In the other, a blend of the larger and smaller particles was used. A developer was then produced by mixing the appropriate toner particles with magnetic carrier particles. In these formulations, the toner particles were positively charged.

Imaging and transfer was performed on the same linear breadboard that was used and described in Ref. 7. In these experiments, a neutral density step wedge was developed by first uniformly charging the photoreceptor with a corona charger. An electrostatic latent image of the step wedge was then formed by contact exposing the photoreceptor through a transparent neutral density target. A visible image was then formed using the technique of Miskinis[27] in the charged area development mode.

Receiver sheets comprised either high quality, highly smooth papers such as Kromekote (a clay coated cast paper) and Ektaflex (a photographic paper base overcoated with polyethylene), or an even smoother film based receiver. The latter was comprised of a nickelized polyethylene terephthalate (PET) support over which was coated 30 μm of TiO_2 powder in a clear polymeric binder and then overcoated with a 2 μm layer of cellulose acetate. Profilometric traces of the surfaces of these receivers show little roughness. For example, the TiO_2/PET receiver showed peaks and valleys having an amplitude of approximately 0.1 μm. Similar peaks and valleys on the Kromekote paper were approximately 5 times larger. The Ektaflex roughness was comparable to that of the Kromekote. For comparative purposes, the same profilometer showed peak amplitudes in the range of tens of micrometers for bond paper.

Transfer was accomplished in one of two manners. In both cases, an aluminum roller with an approximately 6 mm thick coating of doped polyurethane (resistivity ρ approximately 10^{10} $\Omega \bullet$ cm) was used to press the receiver against the toned photoreceptor. The use of the

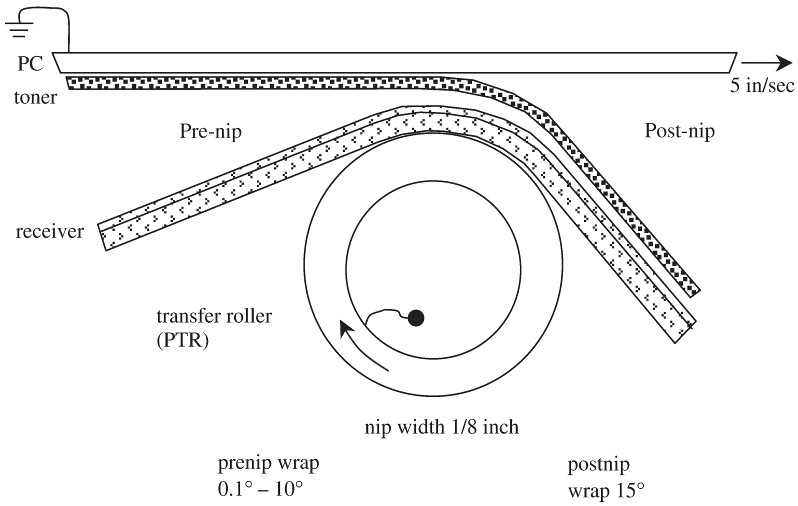

Figure 1. Schematic of the transfer apparatus.

controlled high resistivity polyurethane allowed transfer to be accomplished in a constant current, rather than constant voltage, mode. In the constant current mode, the field depends on the charge density and is independent of the applied voltage and the resistance of the receiver.[28] In the case of the paper receivers, voltages between approximately –1 kV and –8 kV were applied to the aluminum core during transfer. For voltages having magnitudes greater than 8 kV, clear indication of air breakdown was visible in the transferred images. For the PET-based receiver, an electrical bias of up to 500 V was applied directly to the nickel subbing layer and the roller was not biased. Prior to transfer, the photoreceptor was exposed to visible light to erase any residual charge. A schematic of the transfer station is shown in Fig. 1. For both the PET and paper receivers, the applied voltage was limited by pre-nip ionization, which could reverse the polarity of the toner on the photoreceptor, thereby impeding transfer and causing obvious image degradation.

In all instances, the receiver was allowed to follow the transfer roller exiting the nip. This created a post nip wrap angle of approximately 15°, as is shown in Fig. 1. In order to vary Paschen discharge in the pre-nip region, which could alter the toner sign and magnitude of the toner charge prior to transfer, the angle in which the receiver entered the transfer nip was varied. This was accomplished by supporting the receiver in some instances by the breadboard so as to be almost parallel to the photoreceptor, creating a rather shallow angle in the pre-nip region. In other instances, the receiver was wrapped around the roller in the pre-nip region, creating a larger entry angle. The varying pre-nip angles are also reflected in Fig. 1.

Transfer efficiency was measured by using a clear adhesive tape to first remove the residual toner after transfer from the photoreceptor. The transmission densities of the residual and transferred images then were measured as a function of the total density (the sum of the residual and transferred densities) and the ratio determined.

Granularity, which is the quantitative measurement of image noise or graininess, is generally taken, for black and white continuous tone images, to be the standard deviation around a mean image density weighted by a function that represents the spatial frequency response of the human eye to noise. In this study granularity was determined by measuring the standard deviation of the reflection density of the transferred image as a function of reflection density using a microdensitometer with a 400 μm diameter aperture. It should be noted that subsequent to making these measurements, it was determined that a 530 μm aperture more closely simulates the eye-weighted visual graininess. However, the latter can be estimated from the data presented here by multiplying the standard deviations reported herein by the ratio of the two apertures. A full discussion of the relationship between the granularity, as reported herein, the standard deviation of the density, and the Wiener noise spectrum is discussed elsewhere.[29]

The electric field within the transfer nip was estimated using a modified version of the transfer model presented by Zaretsky[30] and Tombs.[31] This will be discussed later in this article.

Results

Representative sections of the transferred and residual images on the TiO_2/PET based receiver for varying ratios of the two size toners are shown in Fig. 2. Figure 2A shows the transferred (left) and residual images made with the pure 2 μm toner. The transfer efficiency at 1.0 ND (neutral density) on the photoreceptor, which corresponds to approximately monolayer coverage with this material, was found to be approximately 84% for the 100% 2 μm toner. Granularity at 0.5 on the receiver was found to be 0.0084. Comparable results obtained using the pure 5 μm toner, as can be seen in Fig. 2B. In effect, images made with either the 2 μm or 5 μm toner transfer very well. It should be noted that neither toner has any sort or silica or other particulate coating on the surface to enhance transfer. Moreover, no release agent such as zinc stearate or Teflon™ had been applied to the photoreceptor.

In contrast, when a mixture of 38% of 5 μm and 62% of 2 μm toner, by weight, corresponding to one 5 μm particle for every 26 toner particles, was transferred, as shown in Fig. 2C, transfer efficiency was found to be limited at 1.0 ND to approximately 34%. The increase in mottle is also quite apparent and granularity was found to have increased to approximately 0.030.

Figure 2D shows the transferred (left) and residual (right) images left on the photoreceptor with a blend of

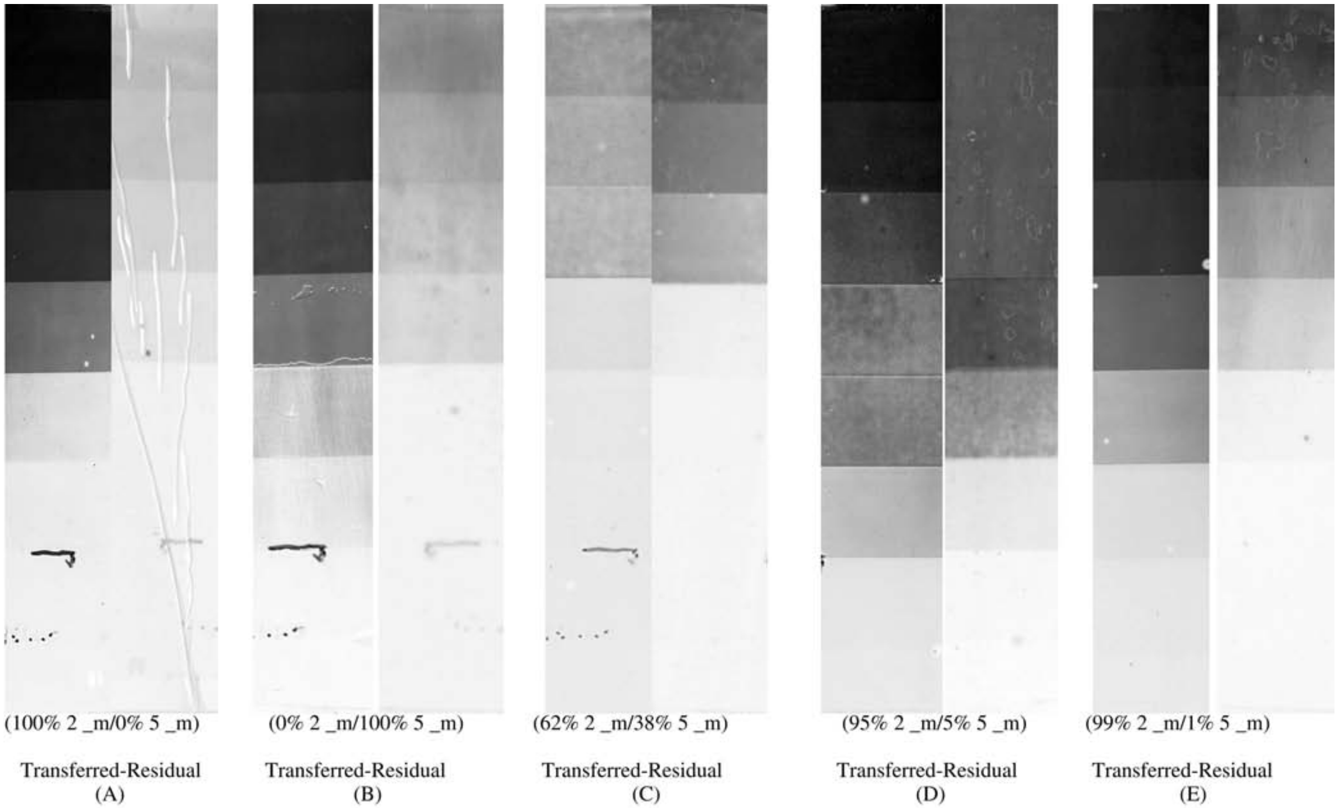

Figure 2. Transferred (left) and residuals (right) of images made with 100% 2 μm toner (2A), 100% 5 μm toner (2B), and a blend of 38% to 62% (2C), 5% to 95% (2D), and 1% to 99% (2E) 5 μm to 2 μm toner.

95% by weight of the 2 μm toner and 5% of the 5 μm toner, which corresponds to one 5 μm particle for every 298 toner particles. The transfer efficiency at a density on the photoreceptor of 1.0 and the granularity at a reflection density of 0.5 on the receiver were 60% and 0.024, respectively.

Figure 2E shows the transferred (left) and residual (right) images made with a developer comprising 99% by weight of the 2 μm toner and 1% of the 5 μm toner, corresponding to just one 5 μm toner particle for every 1,500 toner particles. There is a noticeable degradation in both transfer efficiency (74%) and image quality, as determined by granularity (0.012).

Figure 3 shows optical micrographs of the transferred (left) and residual (right) toned images made using the developer comprising 95% two-micrometer toner particles and 5% of the five-micrometer particles. The apparent lack of focus of the residual toner is due to the fact that one is viewing that toner through a film of clear tape. It is apparent from these micrographs that all of the larger, 5 μm, toner, but only a portion of the smaller, 2 μm, toner transferred, leaving the residual composed solely of the smaller toner. The transfer of some of the smaller particles is, presumably, a result of the finite compliance of the transfer subsystem used in this experiment, coupled with the propensity of the highly spherical particles to readily roll and change their position on the substrate. Rolling is especially possible in light of the occurrence of fringe fields in the vicinity of the transfer nip.

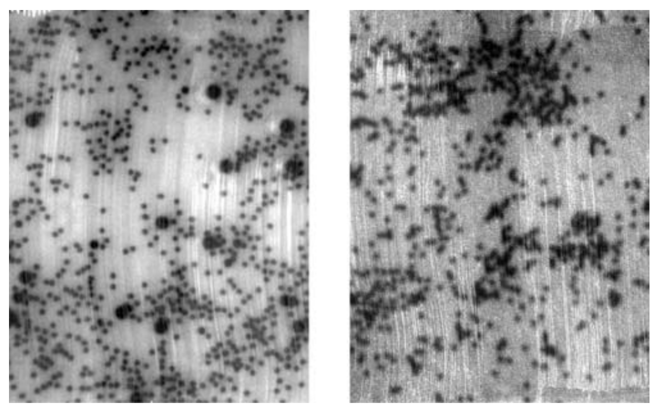

Figure 3. Optical micrographs of the transferred (left) and residual (right) toner made using the developer comprising 95% of the 2 μm toner.

Qualitatively similar results were obtained with the paper receivers, with the most obvious difference being that the transfer tended to occur to the higher portions of the paper surfaces, but not to the recesses. This gave an additional contribution to the grain due to the paper structure. The cause of the image defects due to the paper structure is discussed elsewhere,[3] but arises from the requirement that the toner would need to traverse an air gap, as will be discussed forthwith in connection to the present study. The failure of toner to transfer to the recesses on the surface of the paper can be seen in Fig. 4. This figure shows microdensitometer and profilometer traces over a region of a receiver onto which ground toner having a median volume weighted

TABLE I. Conditions Governing the Electric Fields and Applied Electrostatic Forces Acting on the Toner Particles Transferring to the TiO_2/Nickelized PET Receiver

Poisson: six unknown fields E:

$$\varepsilon_1 E_1 - \varepsilon_2 E_2 = q_{12}$$
$$\varepsilon_2 E_2 - \varepsilon_3 E_{3b} = q_{23} + \rho_3 d_3$$
$$\varepsilon_3 E_{3b} - \varepsilon_4 E_4 = q_{34}$$
$$\varepsilon_4 E_4 - \varepsilon_5 E_5 = q_{45}$$
$$\varepsilon_5 E_5 - \varepsilon_6 E_6 = q_{56}$$
$$E_1 d_1 + E_2 d_2(t) + E_{3b} d_3 + \frac{\rho_3 d_3^2}{2\varepsilon_3} \ldots$$
$$\ldots + E_4 d_4(t) + E_5 d_5 + E_6 d_6 = Vxfer$$

Maxwell stress on toner layer (positive upward):

$$s_3 = \tfrac{1}{2}\varepsilon_0 E_2^2 - \tfrac{1}{2}\varepsilon_0 E_4^2$$

Force of electric origin on toner particle:

$$F_{elec} = s_3 \cdot \frac{\pi\, d^2}{4}$$

Conservation of charge: five unknown surface charge densities q:

$$\frac{dq_{12}}{dt} = J_2 - \sigma_1 E_1$$
$$\frac{dq_{23}}{dt} = -J_2$$
$$\frac{dq_{34}}{dt} = J_4$$
$$\frac{dq_{45}}{dt} = \sigma_5 E_5 - J_4$$
$$\frac{dq_{56}}{dt} = \sigma_6 E_6 - \sigma_5 E_5$$

Initial condition:

$$q_{12}(t=0) = -\rho_3 d_3$$
$$q_{other}(t=0) = 0$$

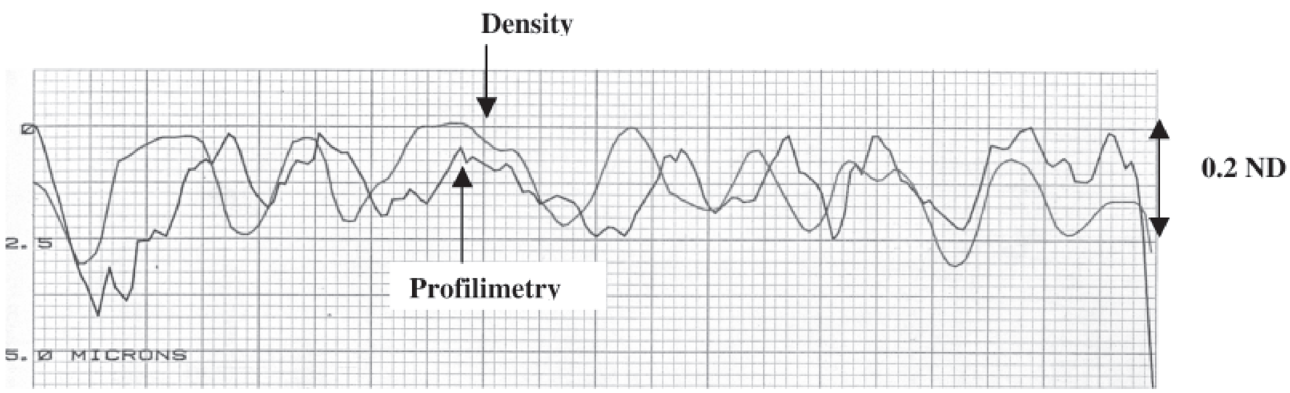

Figure 4. A profilometer and densitometer trace over a section of a paper receiver.

diameter of approximately 12 μm had been transferred, illustrating that the toner only transferred to the high regions of the paper.

Analysis

The experimental results presented in this article can be understood in terms of balancing the surface forces on toner particles in order to effect transfer. The particles themselves are highly monodisperse, as an inspection of Fig. 1 of Ref. 7 will verify. The TiO_2/nickelized PET receiver is extremely smooth by receiver standards. This combination of properties allows, in the cases of pure 2 μm and pure 5 μm toner particles, the particles to contact both the receiver and the photoreceptor, thereby at least partially offsetting the toner adhesive forces to the photoreceptor. The applied electric field would then only have to supply sufficient force to overcome the difference in the toner adhesion to the two surfaces, as discussed in Ref. 3. However, when the image is formed using the blend of larger and smaller toner particles, the larger particles serve as tent poles, which hold the receiver above the smaller toner particles. Under this scenario, the electric field, by itself, would have to be sufficiently strong to overcome the sum of van der Waals and electrostatic forces holding the toner particles to the photoreceptor. There is, of course, compliance in this system so that the receiver can sag enough to contact some of the smaller toner particles. However, as the concentration of the larger particles increases, the amount of sag decreases, thereby reducing the number of smaller particles contacting the receiver and thus impeding their transfer.

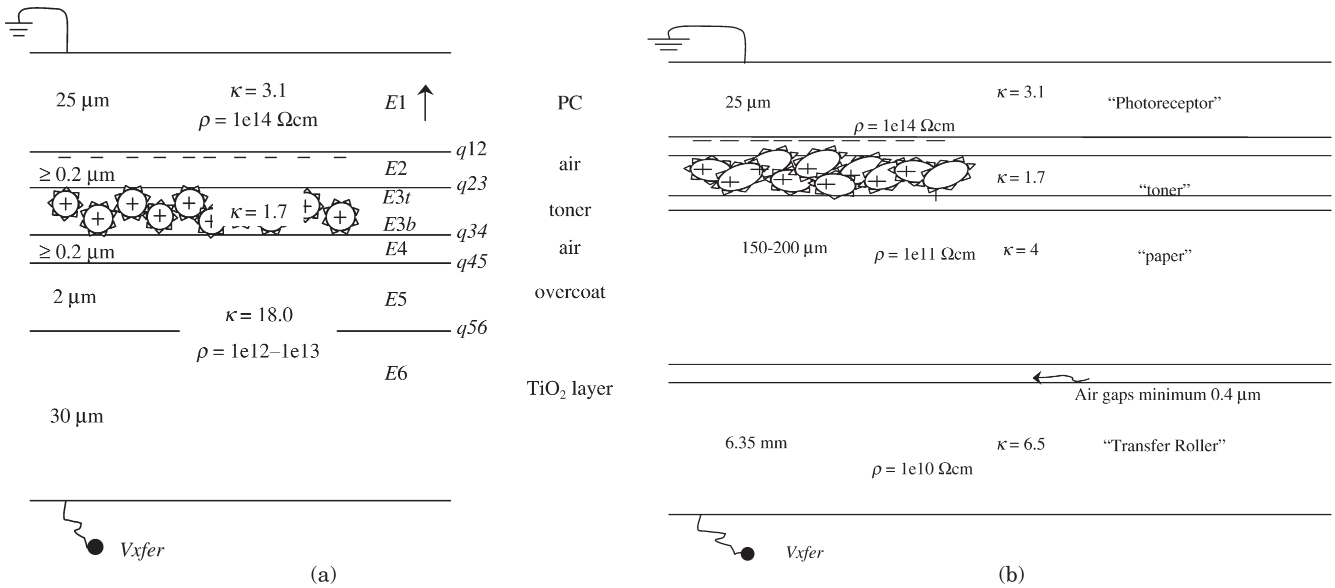

Figure 5. The model used to calculate the applied electrostatic transfer field on the toner for the TiO_2/nickelized PET (5A) and paper (5B) receivers.

This hypothesis can be made more quantitative by comparing the applied electrostatic force on the 2 μm particles to the total force adhering those particles to the photoreceptor. Experimental values of the forces adhering these toner particles to this photoreceptor have been reported in the literature.[7] The applied electrostatic force depends on the toner charge. The measured charge to mass ratio of different developers comprising different batches of 2 μm toner (which also differed in color) ranged from 170 to 500 μC/g. For the 5 μm toner the charge-to-mass was estimated to be 50 to 150 μC/g, based on consideration of the post-development change in the photoreceptor surface voltage, due to the toner layer. It should be noted that, in this particular study, only a single 2 μm toner and carrier were used, even though the mathematical analysis for other values of q/m, in addition to the experimentally-relevant toner, was also performed. The charge-to-mass of the 2 μm toner used in the present experiment was 170 μC/g, corresponding to a particle charge of 7.1×10^{-16} C.

The electrostatic force was calculated using a modified version of the model proposed by Zaretsky[30] and Tombs,[31] as described below.

Figures 5A and 5B show the details of the transfer field model,[30] as applied to the TiO_2/nickelized PET and paper substrates, respectively, that were used in the present study. In effect, the electric field at any point and time in the transfer nip is determined by dividing the region between the two electrodes into a series of layers of differing relative permittivities and resistivities. The field at any point in this structure is determined by solving Poisson's equations, simultaneously with the appropriate charge conservation and initial conditions. The closing and opening of the pre- and post-transfer air gaps drives the dynamics. The force on the particle is then calculated from the Maxwell stress tensor, given by

$$T_{ij} = \frac{1}{4\pi}\left[E_i E_j + B_i B_j - \frac{1}{2}\left(E^2 + B^2\right)\delta_{ij}\right] \quad (3)$$

where E_i and B_i represent the i^{th} component of the electric and magnetic fields, respectively, and δ_{ij} is the Kronecker delta,and was evaluated at the nip exit. The specific criteria for the TiO_2/nickelized PET substrate are given in Table I, with a similar set of criteria used for the paper substrate.

To verify the predictions of the model, the pre-nip ionization voltage was calculated and compared to the experimentally determined values. For the TiO_2/nickelized PET receiver, the onset of pre-nip ionization was calculated to occur at between 600 and 700 volts applied to the nickel layer of the receiver. Experimentally, the onset of pre-nip ionization was observed at approximately 500 volts. For paper, where the bias is applied to the aluminum core of the transfer roller, the onset of pre-nip ionization was calculated to occur at approximately 7,000 volts. Experimentally, the onset of ionization was observed to occur at approximately 8,000 volts. For both types of receivers, the predicted values for the onset of ionization are within reasonable agreement with that observed experimentally, thereby validating the ability of the model to correctly calculate the applied electrostatic fields in the transfer nip region.

Figure 6 shows the calculated electrostatic force (-Felec) for 2 μm, 5 μm, and blended toner. A transfer voltage series is shown for each combination of toner and receiver. Several cases were run at each voltage, to span the probable range of toner charge-to-mass. The hollow triangles indicate high charge, the solid dots low. Other uncertain factors such as paper resistivity and dielectric constant were also varied but had relatively minor effects. As discussed earlier in this article, this result is consistent with transfer occurring in the constant current, rather than constant voltage, mode.

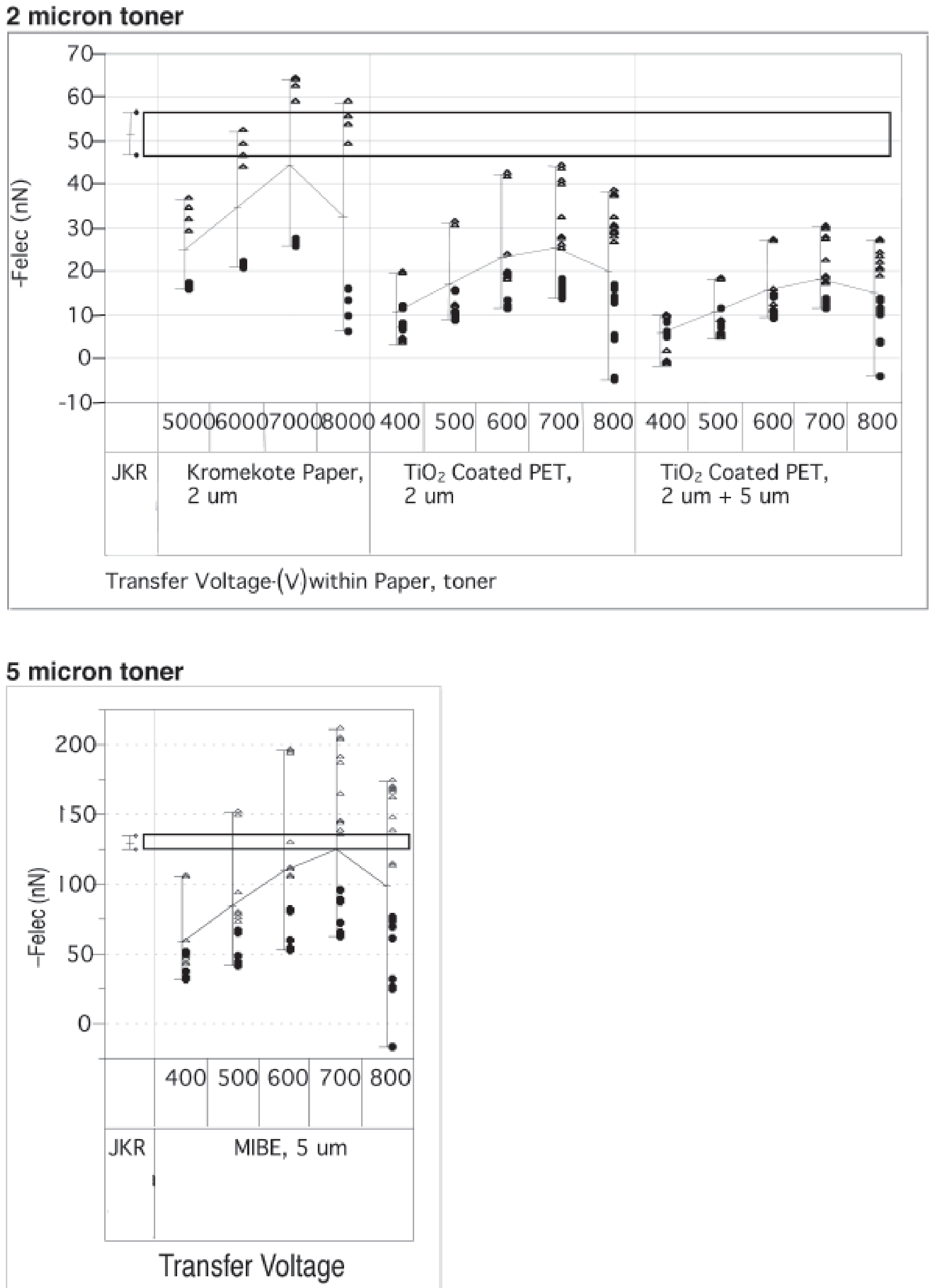

Figure 6. Electrostatic removal force versus adhesion force.

The maximum electrostatic force applied to the 2 μm toner particles used in this experiment were calculated to be approximately 20 and 27 nN for the TiO_2/nickelized PET and Kromekote paper receivers, respectively. The experimentally determined force needed to detach these toner particles from the photoreceptor[7] was reported to be approximately 52 nN. Errors in the measured detachment forces, which would arise principally from errors in the charge measurements, would be less than ± 5 nN. When the 5 μm particles were blended in with the 2 μm toner particles, the calculated force with the TiO_2/nickelized PET receiver was reduced to 15 nN. It is obvious that the applied electrostatic force, by itself, was insufficient to transfer the smaller particles from the photoreceptor to either receiver.

For the 5 μm toner particles, the reported detachment force[7] had been determined to be 130 nN. The model predicts electrostatic force might just be enough to transfer the 5 μm particles if the particle charge were sufficiently great.

The experimentally determined detachment forces and the calculated applied electrostatic transfer forces are plotted in Fig. 6 for the 2 μm and 5 μm toner particles. The experimentally determined detachment forces are shown on the left-hand side of the graphs in the column marked “JKR”. The box shown to the right of that column is the extension of that data range to facilitate comparison with the calculated applied electrostatic transfer forces. The lines in each set of data to the right are the average of the calculated forces for each transfer voltage and receiver.

As proposed elsewhere,[3] in order for electrostatic toner transfer from a photoreceptor to a receiver in the presence of an air gap that separates the toner particles from the receiver to occur, the applied field must be given by

$$qE_{detach} = -\frac{3}{2} w_A \pi R - F_I \quad (4)$$

where q is the charge on a toner particle, E_{detach} is the field needed to transfer the particle, and F_I is the electrostatic force resulting from the formation of an image charge in the photoreceptor. In this context, F_I can be the result of either a uniform or a nonuniform, e.g., a charged patch, charge distribution. It is clear, in the present study, that a sufficiently strong electrostatic field, which is subject to the Paschen discharge limit, to allow the particles to transfer could not be generated.

On the other hand, if the particles were allowed to contact the receiver, there would be a second surface force that would offset the force adhering the toner particles to the receptor.[3] Accordingly,

$$qE_{detach} = -\frac{3}{2} w_A \pi R + k w_A^R \pi R - F_I \quad (5)$$

where $0 \leq k \leq 3/2$. This would reduce the size of the electrostatic force that is needed to transfer the toner particle to the receiver.

The argument presented to explain the present experimental results obviously presupposes that the forces adhering the toner particles to the photoreceptor are due to surface forces, presumably resulting from van der Waals interactions, rather than electrostatic charged patch forces. Because the particles used were spherical and not surface-treated, their presence of asperities and their effect on the occurrence of charged patches should be minimal. Also, since the receiver is electrically insulating, the image force from any charge patches should be considerably weaker on the receiver side as compared to the photoreceptor side of the particle.

Conclusions

It was found that images made with monodisperse spherical toner having diameters of either 2 μm or 5 μm could be transferred electrostatically to a smooth receiver. However, similar images made with blends of these two toners showed a marked decrease in transfer efficiency and corresponding decreases in image quality, as noted by increases in granularity and mottle. These results suggest that electrostatic transfer of these materials occurs, in large part, because surface forces adhering the toner particles to the photoreceptor are offset by similar forces between the toner particles and receivers. These results suggest that, at least for the materials used in this study, toner adhesion to the photoreceptor is dominated by surface, rather than electrostatic, forces.

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References

1. T. A. Jadwin and D. S. Rimai, U.S. Patent #4,517,272 (1985).
2. A. J. Rushing, R. D. Fields, D. S. Rimai, and A. Hoskins, *J. Imaging Sci. Technol.* **45**, 187 (2001).
3. D. S. Rimai and D. J. Quesnel, *J. Imaging Sci. Technol.* **48**, 10 (2004).
4. D. S. Rimai, P. Alexandrovich, and D. J. Quesnel, *J. Imaging Sci. Technol.* **47**, 1 (2003).
5. B. Gady, D. J. Quesnel, D. S. Rimai, S. Leone, and P. Alexandrovich, *J. Imaging Sci. Technol.* **43**, 288 (1999).
6. D. S. Rimai, M. Ezenyilimba, W. K. Goebel, S. Cormier, and D. J. Quesnel, *J. Imaging Sci. Technol.* **46**, 200 (2002).
7. D. S. Rimai, D. J. Quesnel, L. P. DeMejo, and M. T. Regan, *J. Imaging Sci. Technol.* **45**, 179 (2001).
8. V. M. DePalma, *Photogr. Sci. Eng.* **26**, 198 (1982).
9. B. Gady, D. Schleef, R. Reifenberger, and D. S. Rimai, *J. Adhesion* **67**, 291 (1998).
10. N. S. Goel and P. R. Spencer, *Polymer Sci. Technol.* **9B**, 763 (1975).
11. H. Krupp, *Adv. Colloid Interface Sci.* **1**, 111 (1967).
12. D. A. Hays, *Photogr. Sci. Eng.* **22**, 232 (1978).
13. D. A. Hays and W. H. Wayman, *Inst. Phys. Conf. Ser. No. 66: Electrostatics*, 237–242 (1983).
14. D. A. Hays and W. H. Wayman, *J. Imaging Sci.* **33**, 160 (1989).
15. 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*, (IS&T, Springfield, VA, 1994), pp. 142–146.
16. C. J. Mastrangelo, *Photogr. Sci. Eng.* **26**, 194 (1982).
17. L. Nebenzahl, J. Borgioli, V. De Palma, K. Gong, C. Mastrangelo, and F. Pourroy, *Photogr. Sci. Eng.* **24**, 293 (1980).
18. D. A. Hays, in *Advances in Particle Adhesion*, D. S. Rimai and L. H. Sharpe, Eds. (Gordon and Breach Publishers, 1996), pp. 41–48.
19. B. Gady, R. Reifenberger, D. S. Rimai, and L. P. DeMejo, *Langmuir* **13**, 2533 (1997).
20. D. K. Donald, *J. Appl. Phys.* **40**, 3013 (1969).
21. D. K. Donald and P. K. Watson, *Photogr. Sci. Eng.* **14**, 36 (1970).
22. M. H. Lee and A. B. Jaffe, in *Particles on Surfaces 1: Detection, Adhesion, and Removal*, K. L. Mittal, Ed., (Plenum, New York, 1988), pp.169–178.
23. H. Iimura, H. Kurosu, and T. Yamaguchi, *Proc. IS&T's NIP15: International Conference on Digital Printing Technologies*, (IS&T, Springfield, VA, 1999)pp. 535–538.
24. K. L. Johnson, K. Kendall, and A. D. Roberts, *Proc. Roy. Soc. London, Ser. A* **324**, 301 (1971).
25. H. Krupp, Adv. *Colloid Interface Sci.* **1**, 111 (1967).
26. J. W. Vanderhof, M. S. El-Aasser and J. Ugelstad, US Patent 4,177,177 (1979).
27. E. T. Miskinis, *Proc. 6th International Congress on Non-Impact Printing,* (IS&T, Springfield, VA, 1990), pp. 101–110.
28. D. S. Rimai, D. S. Weiss, and D. J. Quesnel, *J. Adhesion Sci. Technol.* **17**, 917 (2003).
29. J. C. Dainty and R. Shaw, *Image Science*, (Academic Press, New York, 1974).
30. M. C. Zaretsky, *J. Imaging Sci. Technol.* **37**, 187 (1993).
31. T. N. Tombs, IS&*T's NIP 14: International Conference on Digital Printing Technologies*, (IS&T, Springfield, VA, 1998), pp. 440–443.