Toner Satellite Formation in Electrostatically Transferred Images

A. J. Rushing▲ and R. D. Fields▲
Heidelberg Digital LLC., Rochester, New York

D. S. Rimai
NexPress Solutions LLC., Rochester, New York

A. Hoskins*
University of Rochester, Rochester, New York

The tendency of toner particles from electrophotographically produced dots and alphanumerics to fly apart during electrostatic transfer was investigated using an ultracentrifuge and an electrostatic detachment cell. It was found that the forces needed to detach a toner particle from a photoconductor were far greater than those that could be applied electrostatically, for all but a few of the particles, either before entering or upon exiting the nip formed by a transfer roller contacting the photoconductor. This suggests that the majority of toner satellite formation should not occur due to toner particles jumping the air gap present in either the pre or postnip regions around the transfer roller. However, it was also found that the forces needed to move toner particles on the photoconductor were at least an order of magnitude less than those needed to detach the particles. This result suggests that toner satellites may be formed by components of the electrostatic transfer forces tangent to the surface of either the photoconductor or receiver or by mechanical forces that move the toner on the substrate either before or after transfer, rather than by inducing the toner to jump across an air gap.

Journal of Imaging Science and Technology 45: 187–197 (2001)

Introduction

Electrophotographically produced images, especially alphanumerics and halftone dots, usually undergo degradation when being transferred from the photoconductor to the final image receiver. These degradations are manifested in many ways: poor transfer efficiency, which results in image mottle and graininess, "hollow character", which is the complete failure to transfer portions of the centers of fine lines, "halo", which occurs when the presence of a high density image on a receiver prevents the transfer of a second color immediately adjacent to the first, etc. One particular form of transfer artifact, that will be discussed in this article, is the formation of "satellites".

In a dry electrophotographic process, an electrostatic latent image is first formed on a photoconductor. The latent image is made visible during the toning process. The image is next transferred to a receiver such as paper. The image-bearing receiver is then transported to the fuser, where it is permanently fixed.

Original manuscript received July 28, 2000

▲IS&T Member

* Present address: Department of Mechanical Engineering, Penn State University, State College, PA.

As is well known, the toner used to develop electrophotographic images consists of highly charged particles. These particles are mutually repulsive, with the repulsive electrostatic interactions extending over relatively long ranges. However, when the particles are contacting each other, the repulsive forces are overbalanced by relatively short-range attractive forces arising from van der Waals interactions.[1–4] Thus, prior to fusing, toner particles residing in dots and alphanumeric characters can be said to be in a state of unstable equilibrium, with any disturbance likely to send at least some of the toner particles flying. These toner particles tend to cluster around the original image and, therefore, can be termed "satellites". An alternative hypothesis suggesting that toner particles do not fly apart due to frictional forces between the toner and the photoconductor has been suggested. However, as the toner is not constrained to move within the plane of the photoconductor, it seems implausible that friction would play a significant role in satellite formation.

An example of the formation of toner satellites around halftone dots is presented in Fig. 1. Figure 1A shows the toned dots on the photoconductor, prior to transfer. As can be seen, the dots appear well formed, fairly uniform is size and shape, and distinctly separate. In addition, there are some isolated particles around each dot. These are satellites. Figure 1B shows a similar array of toned dots on paper after being electrostatically transferred. As is readily apparent, the dots have been badly

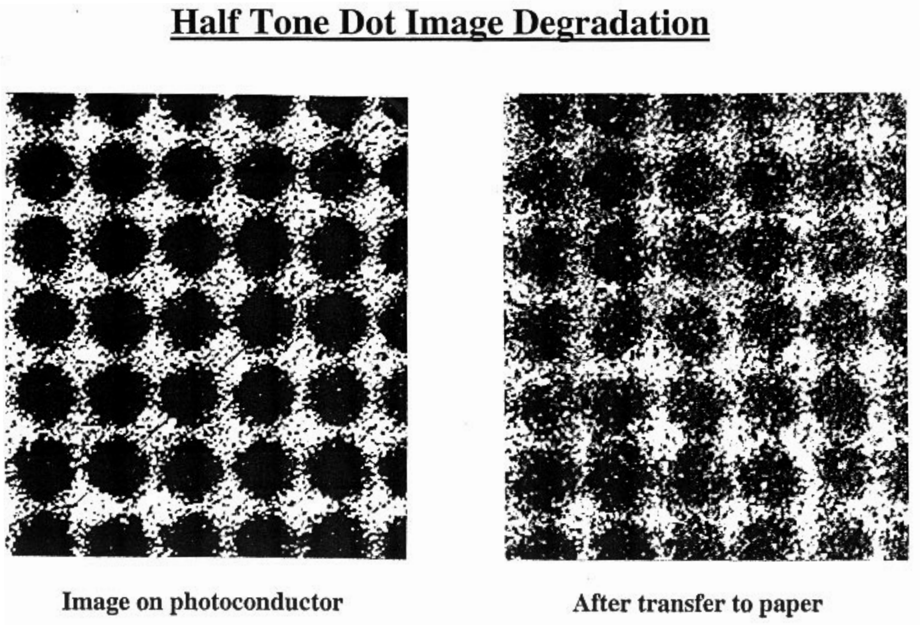
(1A)  (1B)

Figure 1. Toned halftone dots on a photoconductor (1A) and on paper after transfer (1B).

disrupted. There are many more toner particles between the dots and, in some cases, actually cause the boundary between dots to become indistinct. Moreover, the dots are now irregularly shaped and also vary in size. It should be intuitive that such disruptions would adversely affect image quality attributes such as resolution and granularity.

In order to understand the role transfer plays in satellite formation, it is first necessary to consider what actually occurs during the transfer process. An example of that process is presented in Fig. 2. Here, the photoconductor is transported from left to right. The receiver, in this case paper, is wrapped around a biased roller consisting of an aluminum core that had been overcoated with an elastomeric blanket such as polyurethane. This is a typical configuration for a transfer subsystem used in color electrophotographic engines. The toner, transported by the photoconductor, enters the transfer nip formed between the paper and the photoconductor. An electric field, resulting from the potential applied to the transfer roller, builds in the prenip region, reaching a maximum value (which is limited by the Paschen discharge limits of air[5]) within the transfer nip. The toner emerges in the postnip region of the transfer subsystem (hopefully on the paper). However, the Paschen limit of air decreases with increasing air gap size.[6] Therefore, electrostatic discharge can occur at lower field strengths than would be obtained within the transfer nip. Accordingly, it is common that some discharging occurs in the postnip region.

As should be readily apparent, the transfer subsystem offers ample opportunity for satellite formation to occur. There are mechanical disturbances as the photoconductor and receiver are pressed together. These can also include shearing, in the event of overdrive or underdrive in the transfer nip. There are electrostatic forces being applied, electrical discharges, toner migrating, etc.

The seriousness of satellite formation during transfer is evidenced by the amount of research aimed at surpressing it. As examples of such research, Fujita attempted to reduce satellite formation by inserting electrodes to control the shape of the transfer field.[7] Alternatively, Kodama et al. attempted to control satellites using a pretransfer erase.[8] Hypotheses on the causes of satellite formation have ranged from toner particles jumping the airgap in the pretransfer nip,[9] toned images be disrupted by postnip ionization,[7] and the shape of the potential well surrounding the toned image allowing more or fewer satellites to form.[8,10]

In recent years, the drive towards higher image quality has added another complication to the problem of satellite formation. In order to improve image quality, the size of toner particles has steadily declined. In order to enhance transfer, improve flow, and stabilize charge, various so-called “third component addenda” such as surface active silicas, titania, and magnetite have been added to toners over the years.[11] These addenda, in the form of small particles in the tens of nanometers size range, tend

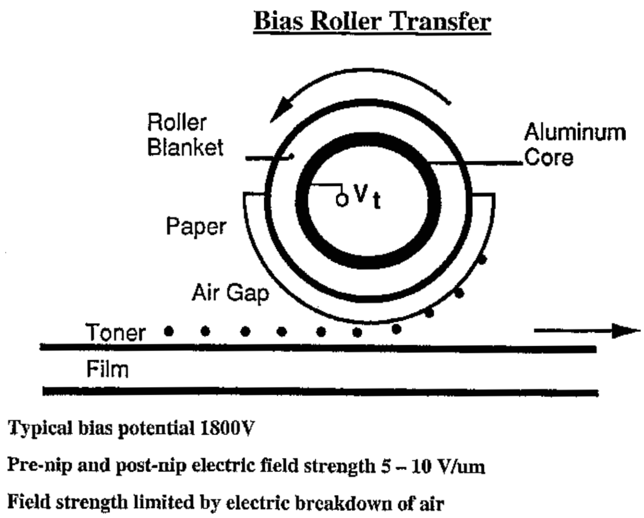


Figure 2. An example of the transfer process and apparatus. The photoconductor is driven from left to right, thereby rotating the transfer roller counterclockwise in this example.

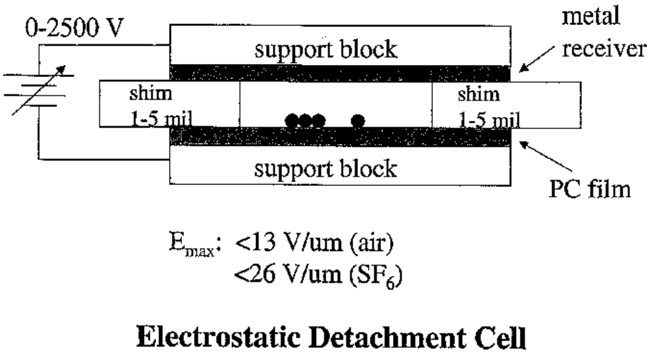


Figure 3. The electrostatic detachment cell.

to coat the toner particles, thereby decreasing their adhesion and cohesion. However, as discussed in Ref. 1, by reducing adhesion and cohesion, the propensity to form satellites is aggravated.

It is clear that, in order to address this image quality related artifact, a mechanistic understanding of toner satellite formation is needed. However, this cannot be readily obtained using a roller transfer subsystem per se. This is because it is difficult to precisely determine under what specific conditions transfer occurs. Rather, it is useful to conduct this type of study using laboratory apparatus designed to simulate transfer under well-defined conditions. It was with these factors in mind that this study was performed.

Experiment

The mechanisms leading to the formation of toner satellites during transfer were studied using an electrostatic detachment cell and an ultracentrifuge. These devices allowed the detachment force of the toner particles from the photoconductor to be determined, as well as simulate transfer conditions under well-defined field strength and gap size.

The ultracentrifuge used in this study was a Beckman LM-70, capable of achieving rotational speeds of 70,000 rpm. When used in conjunction with the 6.5 cm radius rotor, the maximum centrifugal force exerted on the toner particles was about 2,500 nN. Centrifugation was performed at a vacuum of 10^{-2} Torr.

The electrostatic detachment cell, diagrammed in Fig. 3, consisted of polished stainless steel electrodes that were mounted parallel to each other and separated from each other by dielectric shims between 1 and 5 mils thick. A high voltage DC power supply was hooked up across the electrodes. This allowed well defined spacings and fields to be set independently of each other, in contrast to actual conditions in a transfer subsystem. The cell was enclosed in a chamber and hooked up to a fore pump so that electric fields could be operated in air, a low vacuum, or in a controlled atmosphere such as SF_6. The maximum field obtainable before the onset of electrostatic discharging was about 1.3×10^7 V/m in air and about 2.6×10^7 V/m in SF_6. This corresponded to a force of about 200 nN on the toner particles used in this study.

The toner particles were made by grinding and classifying blocks of a carbon containing styrene–acrylate copolymer to an approximately 11 µm volume weighted average diameter, as determined using a Coulter Multisizer. The particles were subsequently surface treated with fumed silica and/or fumed titania. Estimates of the percent of the surface covered by silica, as inferred from SEM micrographs, were between 0 and about 25%. The toner particles, which also contained a a metal chelate charge control agent, were tribocharged negatively against a strontium ferrite core carrier particles with a positive charging silicone resin coating. The median diameter of the carrier particles was about 30 µm. The mixture of toner and carrier particles comprised the developer.

The toner charge was determined using an apparatus consisting of two planar electrodes spaced approximately 1 cm apart. Approximately 0.1g of developer was deposited on one electrode, located above, but in close proximity to, a segmented series of magnets with alternating polarity. An electrometer was connected to the upper electrode. The electrodes were biased in such a manner so as to attract the toner to the upper electrode as the magnets rotated. After all the toner was stripped from the developer, the charge on the upper electrode was determined and the mass of the toner giving rise to that charge was measured. This technique is more fully described elsewhere.[12] Depending on the specific developer used, the charge-to-mass ratio q/m was between –15 and –30 µC/g.

The toner on photoconductor samples needed for the ultracentrifuge and electrostatic detachment cell were prepared as follows. Twelve grams of developer were loaded into a sumpless development station comprising a rotating core of alternating pole magnets and a concentric, rotating stainless steel shell. Development was performed using the so-called "SPD" method, described by Miskinis.[13] The photoconductor used in this study was commercially available and consisted of a typical multilayer structure comprising a conducting layer, a charge generating layer, and a charge transport layer on an Estar (polyethylene phthalate) support.

The conducting layer of the photoconductor was grounded in all instances where toner was being deposited. For samples being prepared for centrifugation, the photoconductor was not charged. Rather, the development station was biased in such a manner so as to deposit less than a monolayer of toner on the photoconductor. Alternatively, when it was necessary to actually form an image, the photoconductor would be charge initially using a grid-controlled corona charger. An electrostatic latent image would be made by contact exposing the photoconductor through a transparent test target that was placed in contact with the photoconductor. The visible image was then produced using discharged area development (DAD). In certain instances where it was necessary to obtain actual transferred images, the image would be electrostatically transferred to paper by pressing the paper and photoconductor together as the photoconductor advanced using an electrically biased transfer roller, located behind the paper. This allowed transfer metrics, such the presence of hollow character and the propensity to generate satellites, to be determined.

The percent removed by either the ultracentrifuge or the electrostatic detachment cell was determined by measuring the area of the photoconductor covered by the toner particles using an optical microscope and image analysis (Image Pro) software before and after the application of the removal force. When performing ultracentrifugation, the photoconductor would be clamped in holders that would, then, be inserted into the rotor. In most instances, the centrifugal force would be normal to the plane of the photoconductor. However, in certain instances, the cells would be rotated in the rotor in

TABLE I. The Tendency To Form Hollow Characters And Satellites As A Function Of Silica Concentration.

Percent Silica	Image Voids (log[void area fraction])	Number of Satellites (RMSGS)
0.00	–1.83	1.36
0.08	–2.11	1.54
0.15	–2.28	1.63
0.35	–2.72	1.85

such a manner so that the removal force would be parallel to the plane of the photoconductor, thereby allowing the force needed to roll or slide, rather than remove, the toner particles to be measured.

The degree of hollow character was determined by measuring the void fraction of transferred alphanumeric characters, as devised by Rakov.[14] In essence, the characters would be electrostatically transferred in a similar manner to that described earlier. The fraction of void area (expressed as the log of the fraction of void area) in the transferred image would then be measured using an image analyzer.

Satellite measurements were also made using an image analyzer. In this instance the number of satellites was determined using the method of Edinger,[15] based on determining the root mean square (RMS) of the *GS* number, of Dooley and Shaw,[16] as shown in Eq. 1 where

$$GS = \left(C\, n\, d^4\right)^{1/2}$$

where n and d represent the number of particles per square millimeter and the diameter of the particle in micrometers, respectively, and C is a constant that is equal to 4.74×10^{-6}. The GS number, $GS = (Cnd^4)^{1/2}$ where C is the constant 4.74×10^{-6}, d is the average particle circular diameter in micrometers, and n is the number of particles per square mm. The readers are referred to Ref. 15 for further discussion.

Results

Although the cause of hollow character is not fully understood, there is evidence that it may be the result of cohesive interactions between toner particles causing them to stick together during transfer and adhere to the more adhesive surface, which is often the photoconductor.[17] If, as had been proposed,[1] the role of addenda such as silica is to reduce adhesion by serving as physical spacers between the toner particles and the photoconductor, they should also reduce cohesion between toner particles. Accordingly, there should be less hollow character and more toner satellites as the silica concentration increases. This correlation is shown in Table I.

Several points in this table are especially worth noting. The formation of hollow character is expressed as the log of the fraction of the area of the alphanumeric where absolutely no toner transferred, thereby leaving a white spot. This total lack of transfer is characteristic of hollow character. A log void fraction of –1.0 means that 10% of the alphanumeric failed to transfer—a defect that would be clearly visible. A log void fraction of –2.0 means that 1% failed to transfer and a log void fraction of –3.0 means that only 0.1% of the character shows voids due to a failure to transfer. While the specifics of the amount of hollow character formation is subject to specific process conditions, the relative comparison presented here is still valid. It is quite clear that the amount of hollow character clearly decreases with increasing silica concentration. Conversely, as the amount of hollow character diminishes, the degree of satellite formation clearly increases. As satellites can result in a loss of sharpness and resolution, increased granularity, and more background, it is clear that the amount of silica and the process conditions affecting these two defects must be carefully controlled and balanced for optimal image quality.

In order to be able to optimize the transfer process so as to minimize the formation of satellites, it is first necessary to understand how satellites are formed. As previously discussed, several hypotheses have been proposed.

One hypothesis suggests that toner particles, especially in halftone dots and alphanumerics, reside in a potential well due to a repulsive potential on the photoconductor existing in the untoned regions. While this may be the case for DAD development, where the toner is deposited in the discharged areas of the photoconductor, it is certainly not true for charged area development (CAD), as is generally performed in optical copiers. Moreover, one need merely compare the dot structures on the photoconductor and receiver, as presented in Figs. 1A and 1B, to realize that the potential well hypothesis cannot account for the majority of satellites. Specifically, as discussed, these images were formed in the DAD mode. In order to produce the photomicrographs, the photoconductor had to be exposed. Obviously, it would be difficult to know precisely how well the dots were formed or how many satellites were present without illuminating the photoconductor. The satellites visible in Figure 1A could have come from a variety of sources including development, transport and handling of the toned photoconductor, or, indeed, simply from discharging the potential well. However, upon comparing Figs. 1A and 1B, it is clear that the preponderance of satellite formation on the receiver occurred in association with the transfer process.

As discussed earlier in this article, it has also been proposed that satellite formation can arise from the toner jumping across the air gap before entering the transfer nip. To do this would require that the applied electrostatic transfer force be sufficiently strong to be able to separate the toner from the photoconductor. The size of that force can be readily ascertained using an ultracentrifuge. These results are shown in Fig. 4. As can be readily seen, the force needed to remove a given percentage of toner decreases monotonically with increasing silica concentration. This is consistent with the results reported by Gady and co-workers[1] and Iimura and co-workers.[18] In contrast to the results reported by Iimura and coworkers, however, there was no clearly observed dependence of the removal force on the toner charge-to-mass (q/m). For example, the force required to remove half the amount of a nonsurface treated toner with $q/m = -31.3$ μC/g that had been freshly deposited, was about 550 nN. To remove a similar amount of the same toner, but with a lower value of $q/m = -23.5$ μC/g, after allowing it to reside on the photoconductor for 7 days was approximately 1000 nN. In general, it appeared that the separation force depended more on time than on toner charge. Further studies are needed to more fully understand the effects of time and charge on toner adhesion. In addition, if the samples were first installed in the centrifuge in such a manner so that the centrifugal force tended to drive the toner particles into the photoconductor, it subsequently took a higher force

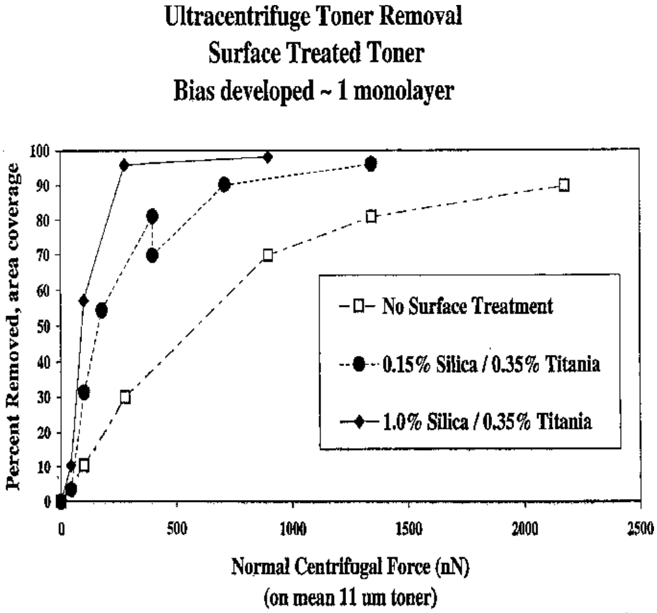


Figure 4. The percent of toner removed from the photoconductor, as a function of the applied centrifugal force.

to separate those toners. These results suggest that plastic deformations may be occurring due to the stresses associated with the adhesive forces. Indeed, adhesion induced plastic deformations of toner-like particles on silicon substrates has been reported.[19] If this is correct, it is important that adhesion measurements be taken as soon after the toner has been deposited on the photoconductor as possible and all measurements be taken within consistent time intervals. In these studies the time between the toner deposition and centrifugation was minimized. Samples were generally run within two hours of preparation and, in all instances, centrifugation occurred the same day the toner was deposited. Samples subjected to electrostatic detachment were run in time periods less than about 2 h.

There has been a long-standing debate in electrophotography concerning the types of interactions governing the adhesion of toner particles to photoconductors. Specifically, there is a question as to whether toner adhesion is dominated by van der Waals interactions or by electrostatic forces caused by localized distributions of charges, or so-called "charged patches".[20] A conclusive resolution of this issue is beyond the scope of this article. However, it is worthwhile to consider which of these two mechanisms is most likely to be most significant for the toners used in this study.

First, let us consider the toner particles without surface treatment and assume that the adhesion arises from van der Waals interactions. The force F_S needed to separate a particle of radius R from a substrate is obtained from JKR theory[21] according to

$$F_S = -\frac{3}{2}\pi\, w_A\, R \tag{1}$$

where w_A is the thermodynamic work of adhesion. It is seen from Fig. 4 that the approximately half the toner was removed from the photoconductor upon application of a centrifugal force equal to about 600 nN. The work of adhesion, calculated from Eq. 1, is then determined to be approximately 0.023 J/m^2. This is a very reasonable value for a styrene acrylic particle in contact with a polyester substrate.

The charged patch model has estimated the separation force by assuming that, if the attractive force is balanced by an externally applied removal force, separation would occur.[20] This assumption is, strictly speaking, incorrect as it does not take into account the work needed to overcome the deformations of the materials arising from contact stresses. A correct analysis of the separation force under the influence of electrostatically charged patches is beyond the scope of this article. Therefore, we will follow the more common approach.

The electrostatic force of attraction F_E of a particle, with a localized charged patch of charge density σ confined to an area A_C, to a substrate is given by[20]

$$F_E = \frac{\sigma^2 A_C}{2\varepsilon_0}\ . \tag{2}$$

In order to use this relationship, it is important to know A_C. Unfortunately, this has not been determined for this particular toner. However, Eklund and co-workers[22] and Bowen and co-workers[23] have reported experimentally determined contact area measurements of ground toner particles. Both groups report values of A_C to be of the order of 5 – 10% of the cross-sectional area of the toner. Assuming a contact area of 5% of the cross-sectional area, one finds that it is necessary that $\sigma = -1.5 \times 10^{-3}$ C/m^2 if F_E = 600 nN. The total charge in this area would be -7.1×10^{-15} C, or 1/3 of the total charge on the toner particle. This is not very likely. Moreover, the field associated with this charge, approximated by

$$E = \sigma / \varepsilon_0 \tag{3}$$

would be 1.7×10^8 V/m, which is very high.

Even at this point, there are several logical inconsistencies. In order to validate the charged patch model, it is first necessary to explain why van der Waals forces, which seem to be in apparent agreement with the measured separation forces, would actually be much smaller. This is done by assuming that the toner rests on sharp, highly charged asperities having very small radii of curvature. However, this assumption appears in conflict with the actual aforementioned contact area measurements. Moreover, if we assume that the contact area is significantly smaller that what has just been assumed, the estimated electric field would have to be correspondingly higher. This would not appear to be feasible. Accordingly, it would appear that the adhesion of the toner to the photoconductor for the toner without silica is dominated by van der Waals interactions. However, as discussed by Gady and co-workers,[1] the electrostatically charged patches would appear to become more important with increasing silica concentration, as the effect of van der Waals interactions are weakened.

The force needed to detach toner particles from the photoconductor is also seen to decrease with increasing silica concentration. At 0.15% silica, half the toner appears to detach upon application of a force of about 200 nN. This decreases to about 100 nN at 1.0% silica. These results are qualitatively in agreement with the results of Gady and co-workers[1] and Iimura and coworkers,[18] with quantitative differences, presumably, ascribable to the specific properties of the toner and photoconductor. A force of about 50 nN was sufficient to detach only about

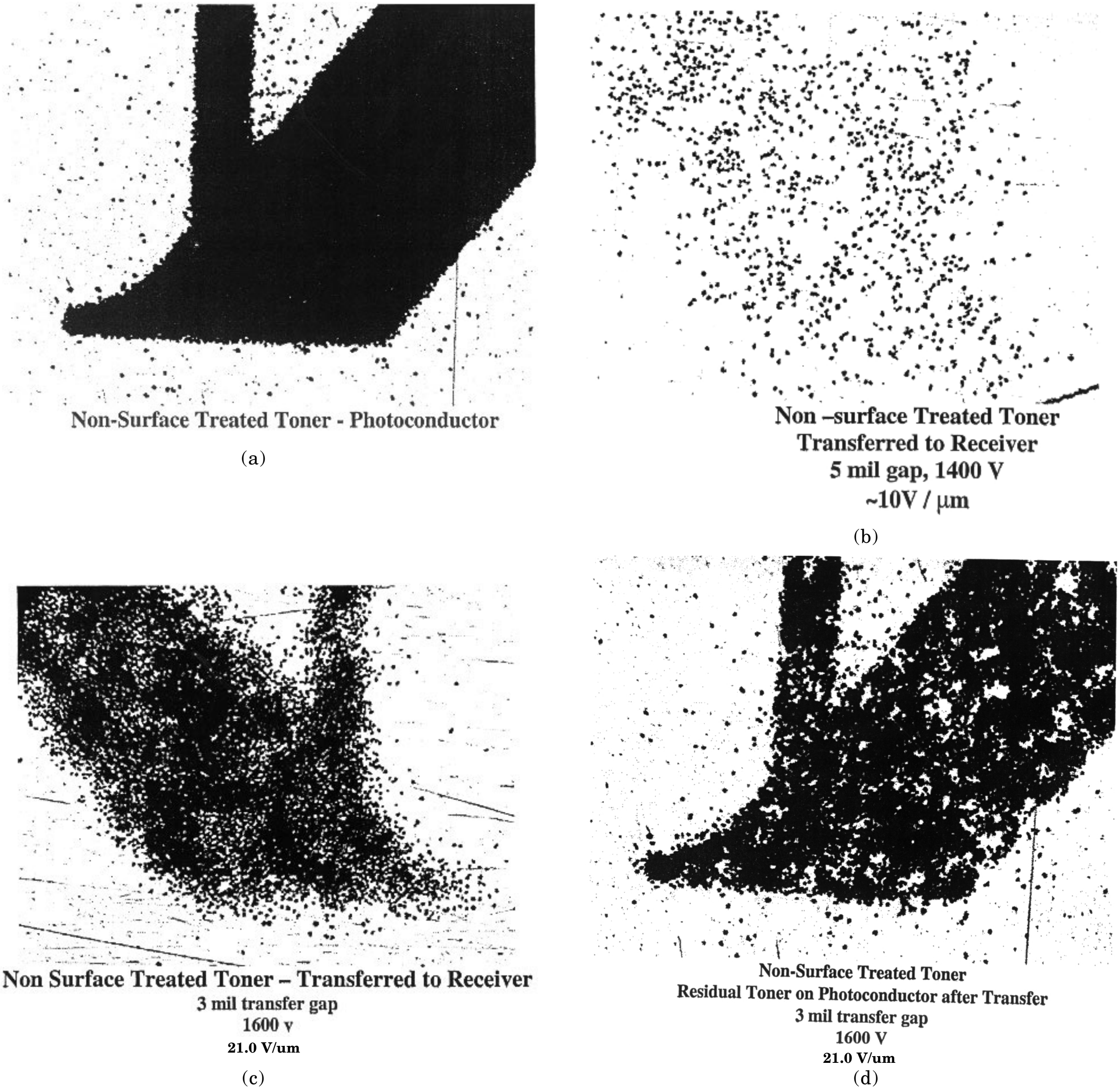


Figure 5. The effect of an electrostatic field on toner gap jumping for toner with no silica. (a) a portion of the letter "N" on a photoconductor; (b) The fraction transferred to an electrode spaced 5 mils away at a field of 10^7 V/m; (c) Fraction transferred to an electrode spaced 3 mils away at a field of 2.1×10^7 V/m; (d) Fraction remaining on the photoconductor, corresponding to transfer conditions in 5C.

10% of the most highly silica-treated toner and insufficient to detach any significant amount of either of the other toners.

Let us now consider how the size of the detachment forces and the amount of silica on the surface of the toner particles affects the ability of toner particles to traverse an air gap in the pre-transfer nip region. As previously discussed, as the gap between the receiver and photoconductor closes as both approach and begin to enter the transfer nip, the electrostatic transfer field builds, but is limited by the Paschen strength of air. As is well known, this limit decreases with increasing air gap. In this instance the size of the air gap is fixed by the toner at about 11 µm, as well as the paper roughness, corresponding to a Paschen limit of about 3.5×10^7 V/m. However, just outside the nip, the Paschen limit is correspondingly lower. For example, when the separation of the receiver from the photoconductor is about 30 µm, the Paschen limit is reduced by more than half, to about 1.5×10^7 V/m. Thus, even at relatively small separation distances in the prenip region, the maximum electrostatic force that can be exerted on a toner particle having a q/m ratio of –31.3 µC/g, such as the uncoated toner used here, would be about 330 nN, which should be sufficient to detach only about 1/3 the toner from the photoconductor. For toners with lower charges, the applied force would be correspondingly less. The effect of electric field and electrode separation was determined using the electrostatic detachment cell.

Figure 5a shows a portion of a letter "N" developed using toner without silica. As is apparent, there are some satellites present even before transfer. As to whether these satellites occurred during development or from handling the image-bearing photoconductor could not be determined. Figure 5b shows the toner transferred across a 5 mil wide air gap to a stainless steel electrode at a field of about 10^7 V/m, corresponding to an average force of about 310 nN. As expected, there is little toner detached from the photoconductor under these forces. Figure 5c shows the toner that transferred to the stainless steel electrode across a three mil wide gap by a field of 2.1×10^7 V/m, which corresponds to an average force of 462 nN. It is seen from Fig. 4 that, upon application of a force of this magnitude, about 35% of the toner should detach. By comparing the amount detached to the residual on the photoconductor (Fig. 5d) it is seen that, indeed, about 1/3 of the toner transferred. However, these large forces would not typically be expected in the pre-transfer nip region. Rather, the fields in that region, as estimated using the means discussed by Zaretsky,[24] should be only of the order of a few volts per micrometer at most. Accordingly, there should be little toner without silica treatment jumping across an air gap in the pre-transfer nip region.

It would be expected that the application of silica to the surface of the toner should facilitate traversing an air gap. This is clearly demonstrated in Figs. 6 and 7 which show the original toned image (A), the transferred image (B) and the residual image on the photoconductor after transfer at fields of approximately 10^7 and 2.0×10^7 V/m, respectively. It is readily apparent, upon comparing Figs. 6 and 7 with Fig. 5 that the silica treatment facilitates the air gap jumping of the toner. In fact, it would be expected from the centrifugal measurements that, at the two fields used, approximately 35% and 70%, respectively, of the toner should jump across the air gap. By comparing the transferred to residual toner, it is apparent that this is approximately the amount transferred. Thus, the electrostatic and centrifugal measurements appear to be in good agreement. Again, these fields are fairly high and would be more typical of those found within the transfer nip rather that in the pre-transfer nip region.

In order for satellites to form during transfer, it is important that the toner particles jump from where they are originally located to another site. This might occur, for example, due to the Coulombic repulsion between particles. If the principal mode of satellite formation were toner particles jumping across the air gap present in the pre-transfer nip region, one might expect the range at which satellite particles to be found to increase with decreasing adhesion. Accordingly, it might be expected to find more toner particles at farther distances from the source of the toner with surface-treated toners than without. This hypothesis was tested in the electrostatic detachment cell. Halftone dots corresponding to a 5% tint were developed using toners without surface treatment and with 1.0% silica/0.35% titania. The diameter of the target radius was approximately 115 μm. The developed images showed little dot gain and were comparable in size to the target dots. The dots were then "transferred" in the detachment cell, with 2,000 V applied across a 5 mil spacing, and the percent of area covered by toner was measured. These results are shown in Figs. 8 and 9 for the untreated and surface treated toners, respectively. Upon comparing these two figures, it is immediately obvious that more of the surface treated toner particles were able to traverse the air gap, as expected. However, outside the actual toned areas, the amount of toner appears to be equal for the two cases. For example, at a distance of 150 micrometers from the center of the dot, about 20% of the area is covered by toner for either of these two toners. Moreover, there was virtually no toner in either example beyond 225 micrometers from the center.

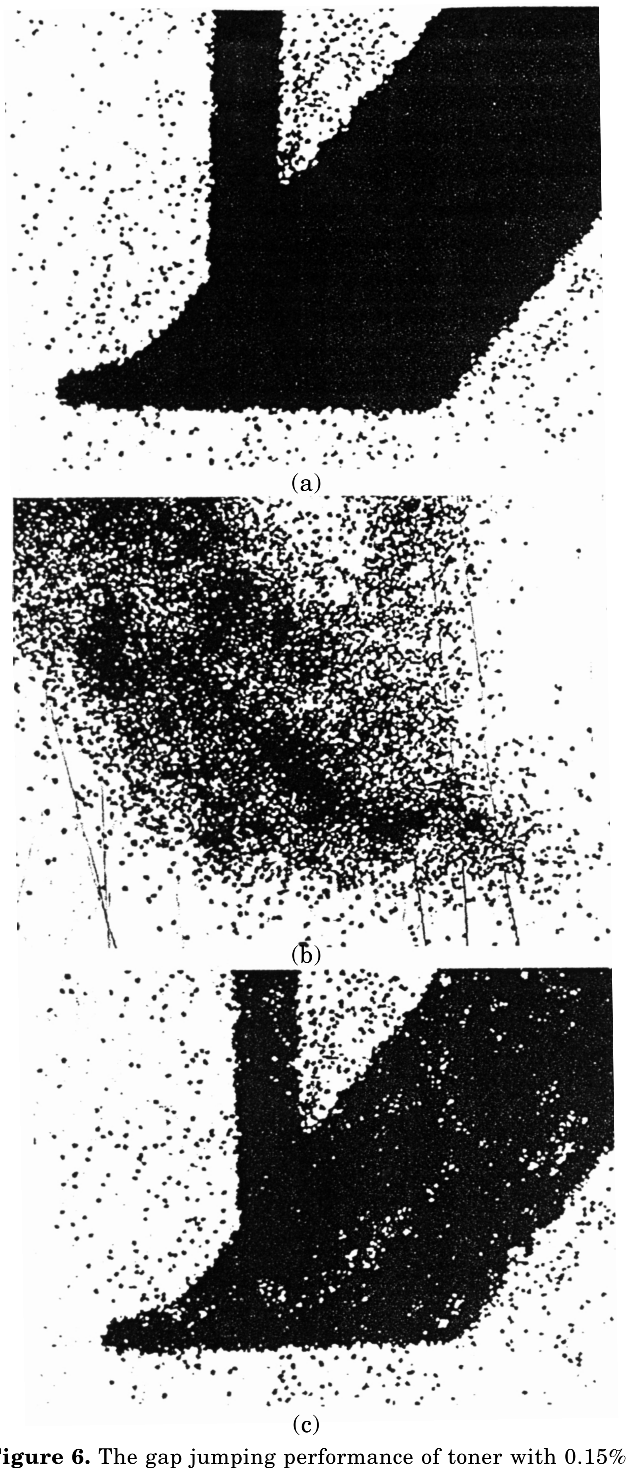


Figure 6. The gap jumping performance of toner with 0.15% silica by weight at an applied field of approximately 10^7 V/m. 6a, 6b, and 6c show the original image on the photoconductor, the transferred, and the residual material, respectively.

This result might seem, at first, contradictory to those reported in Ref. 1, which reported an increase in satellite formation with an increase in silica concentration. However, that study was done under actual transfer con-

(a)
(b)
(c)

Figure 7. The gap jumping performance of toner with 0.15% silica by weight at an applied field of approximately 2.0 × 10^7 V/m. 6a, 6b, and 6c show the original image on the photoconductor, the transferred, and the residual material, respectively.

ditions, whereas the present study was done under more ideal circumstances. However, the present study suggests that something other than jumping across an air gap is the cause of satellite formation during transfer.

As previously mentioned, another hypothesis suggests that satellite formation is due to ionization present as the receiver and photoconductor begin to separate after transfer. To test this theory, small pieces of 1 mil thick shim stock were introduced underneath the photoconductor in order to raise certain localized regions in the

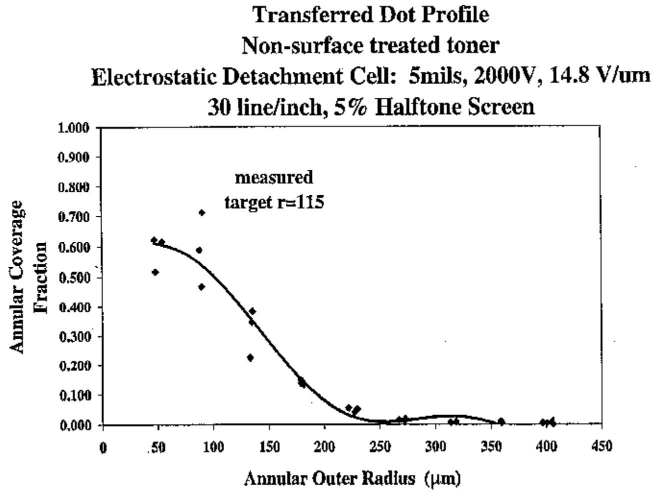


Figure 8. The percent of the area covered by toner, without any surface treatment, as a function of distance from the center of a halftone dot having a radius of 115 μm.

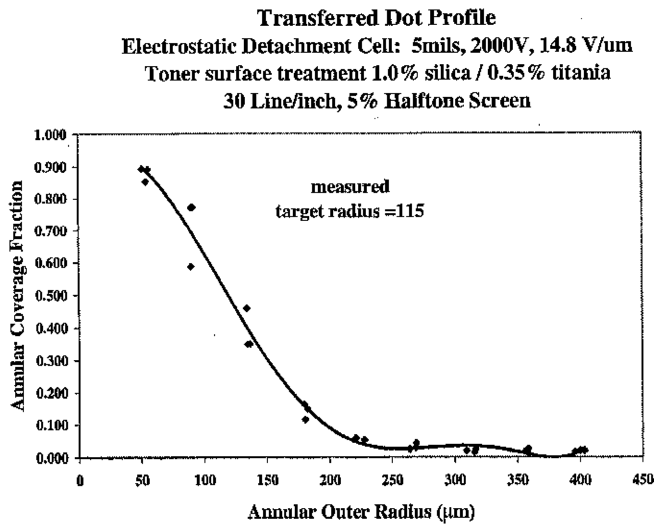


Figure 9. The percent of the area covered by toner, with a surface treatment comprising 1.0% silica and 0.35% titania, as a function of distance from the center of a halftone dot having a radius of 115 μm.

vicinity of an image. A potential was then applied and increased until localized electrostatic discharges were observed in the region of the raised areas. The receiver and photoconductor were then separated and the receiving electrode examined for satellites. The number of satellites was found to be approximately the same with or without the presence of the shims, suggesting that postnip ionization, by itself, is not a cause of satellites.

If neither prenip air gap jumping by the toner or postnip ionization appears to be able to account for transfer satellite formation, what can account for it? In the course of handling pieces of the image-bearing photoconductor, it was found that small mechanical perturbations could significantly disrupt an image. For example, a small finger flick on the photoconductor would result in significant number of satellites. These observation, together with the separation force measurements, suggest that satellite formation may not be

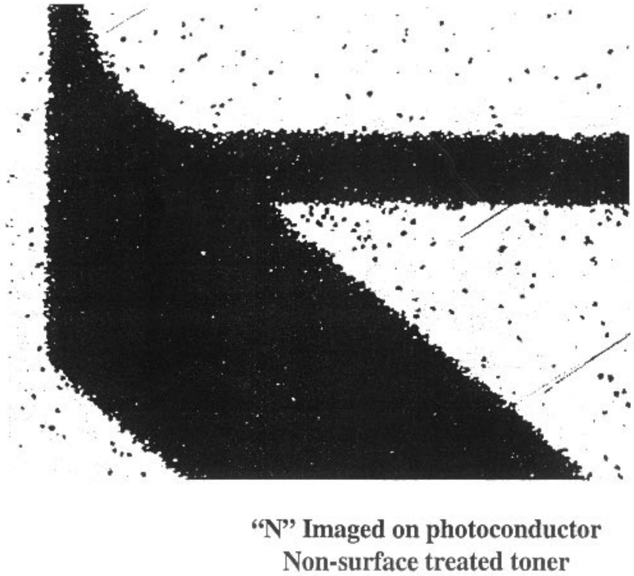


Figure 10. A 12 pt. letter "N", developed using toner with no surface treatment, on a photoconductor.

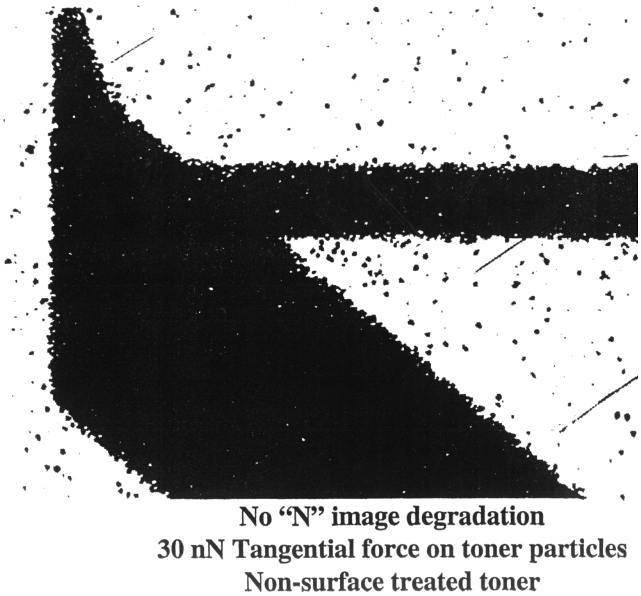


Figure 11. A 12 pt. letter "N", developed using toner with no surface treatment, on a photoconductor, after subjecting the toner to a force of 30 nN parallel to the plane of the photoconductor.

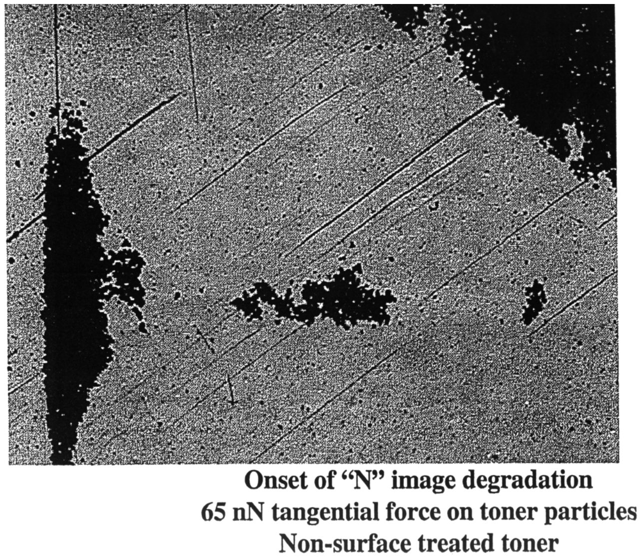


Figure 12. A 12 pt. letter "N", developed using toner with no surface treatment, on a photoconductor, after subjecting the toner to a force of 65 nN parallel to the plane of the photoconductor.

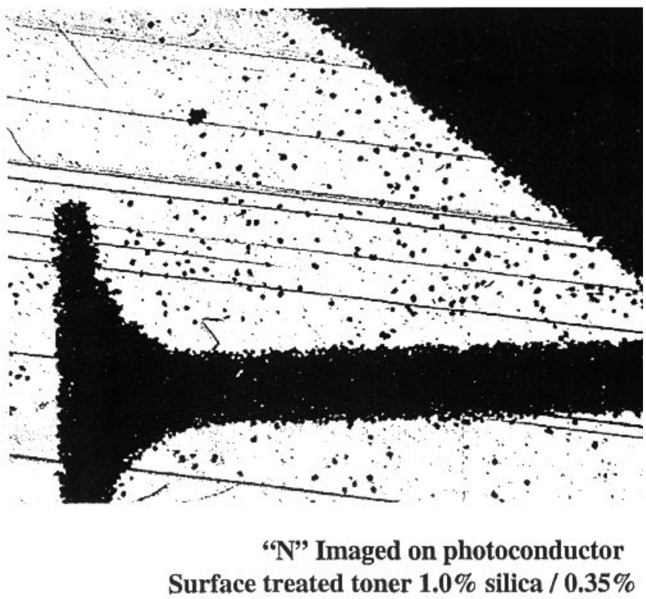


Figure 13. A 12 pt. letter "N", developed using toner with a surface treatment consisting of 1.0% silica/0.35% titania, on a photoconductor.

associated with the toned images separating from the underlying substrate. Rather, satellites may form by the movement of the toner particles while remaining in contact with the substrate. In other words, satellites might form due to the sliding or rolling motion of toner particles. If this is to occur, the force needed to slide the toner particles would have to be significantly less than that needed to detach them.

To test whether the sliding hypothesis was feasible, samples comprising the 12 pt. letter "N" were toned on a photoconductor. The photoconductor was then loaded into the ultracentrifuge. However, in this instance, the sample holders were oriented in such a way so that the centrifugal force was in the plane of the photoconductor. The results of this experiment are shown in Figs. 10 through 12 for toner without any surface treatment, and in Figs. 13 through 15 for toner comprising 1.0% silica/ 0.35% titania.

Figure 10 shows a micrograph of a portion of the "N" prior to centrifugation. Figures 11 and 12 show the "N" after being subjected to a shearing force of 30 nN and 65 nN, respectively. As can be seen, there is little toner disruption caused by the 30 nN shear force. However, the application of 65 nN was sufficient to cause moderate disruption of the toner, due to the sliding of the toner particles on the photoconductor. The size of the shear force needed to dislocate the toner and cause image disruption is about an order of magnitude less than the force needed to separate the toner from the photoconductor. Similar results were obtained for the surface

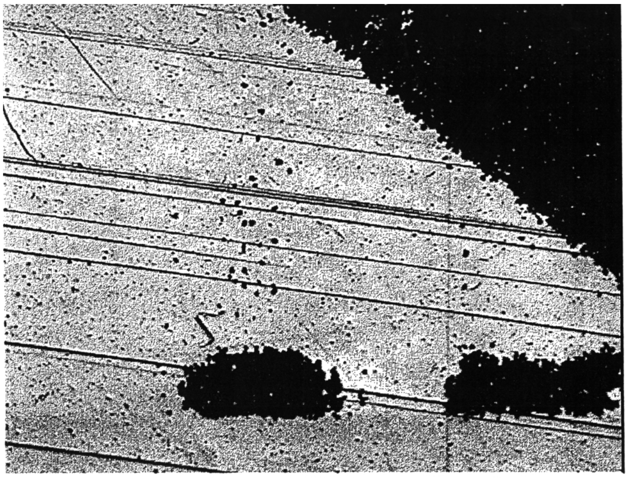


Figure 14. A 12 pt. letter "N", developed using toner with a surface treatment consisting of 1.0% silica/0.35% titania, on a photoconductor, after subjecting the toner to a force of 30 nN parallel to the plane of the photoconductor.

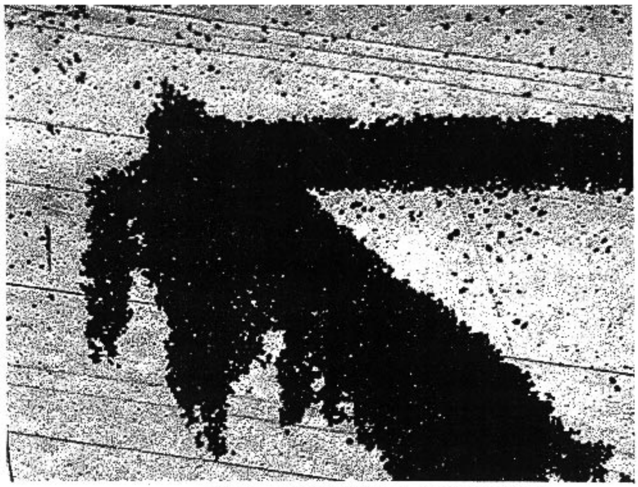


Figure 15. A 12 pt. letter "N", developed using toner with a surface treatment consisting of 1.0% silica/0.35% titania, on a photoconductor, after subjecting the toner to a force of 45 nN parallel to the plane of the photoconductor.

treated toners, but with smaller shear forces, as evidenced by Figs. 13 through 15. Figure 13 shows the surface treated toner on the photoconductor prior to the application of any shear force. Upon application of a 30 nN shear force, (Fig. 14), noticeable image disruption, comparable to that occurring in the untreated toner at 65 nN, is observed. With a shear force of 45 nN, the disruption is quite severe, with the main body of the letter "N" being disrupted. As before, the size of the shear force needed to disrupt the image is about an order of magnitude smaller than that needed to detach the toner. Moreover, it requires only about half the shear force to disrupt the image formed with the surface treated toner than it does to cause comparable disruption to images formed with the untreated toner.

These results suggest that the formation of toner satellites is more likely to occur by toner sliding (or rolling, if the toner is sufficiently spherical) on the photoconductor or receiver prior or after transfer. It is acknowledged that, of course, there are a multitude of toners with different surface treatments and made from a variety of polymers. These variations are likely to cause differences in the adhesion and electrostatic forces that can impact the formation of satellites. Accordingly, it cannot be read into these results that all toners will respond in a similar manner to the ones studied. In addition, there is a myriad of photoconductors available. These, too, can affect adhesion. How general, then, are the results obtained in this study? While this question cannot be conclusively answered without an in-depth study of a wide range of materials, several comments can be made. The toner particles used here are rather large and, in some instances, contain rather high concentrations of silica. Toners used today are often smaller and contain lower surface area coverages of silica. As electrostatic effects become more significant over van der Waals interactions for larger particles with higher surface treatment concentrations, it would be expected that the toners used in this study would be more likely to jump air gaps than would be the case for smaller ones. Certainly, the adhesion forces measured are well within line with those reported by others in the literature. In addition, the photoconductor used is a typical, commercially available, organic photoconductor. The choice of materials suggests that the physics controlling toner movement in this study is fairly typical of most toners and should be reasonably representative.

Assuming that satellite formation does occur due to sliding of the toner on the substrate, what are the sources of the shear forces? These can arise from a variety of sources, including tangential components of the transfer field in the pre-transfer nip region, nonuniform fields associated with the pre- and post-nip regions of the transfer roller, dielectrophoretic forces, the presence of ground planes, or simple mechanical vibrations. The possibility of air currents due to air breakdown disrupting the toner particles has also been suggested.[25] Considering that the forces needed to slide toner particles are rather small, it should not be hard to generate them.

Conclusions

Although some satellite formation can occur due to pre-transfer nip gap jumping or post-transfer nip electrostatic discharging, the ease with which toner particles can be slid or rolled suggests that most toner satellites may be caused by shear forces acting on the toner. Whether or not this is the mechanism of satellite formation in an actual electrophotographic engine and, if so, what specifically are the origins of the forces, remains to be determined. Moreover, as the amount of surface treatment of toner increases, the propensity to form satellites also increases, although the amount of hollow character decreases. Finally, toner adhesion seems to be dominated by van der Waals interactions, rather than by electrostatically charged patches, although the presence of such charged patches will increase the force needed to separate the toner from the photoconductor.

Acknowledgment. The authors would like to thank Sue Clark, Ray Edinger, Barrett Gady, Sal Leone, Gloria McCall, and Frank Reitze for their valuable assistance.

References

1. B. Gady, D. J. Quesnel, D. S. Rimai, S. Leone, and P. Alexandrovich, *J. Imag. Sci. Technol.* **43**, 288 (1999).
2. B. Gady, R. Reifenberger, D. S. Rimai, and L. P. DeMejo, *Langmuir* **13**, 2533 (1997).
3. B. Gady, R. Reifenberger and D. S. Rimai, *J. Appl. Phys.* **84**, 319 (1998).
4. B. Gady, D. Schleef, R. Reifenberger, and D. S. Rimai, *J. Adhesion* **67**, 291 (1998).
5. F. Paschen, *Wied. Ann.* **37**, 69 (1889).
6. J. D. Cobine, *Gaseous Conductors*, Dover Publications, New York, 1957.
7. H. Fujita, U.S. Patent 5,825,384 (1998).
8. H. Kodama, Y. Ohno and K. Sakatani, U.S. Patent 5,966,560 (1999).
9. T. N. Tombs and R. R. Bucks, unpublished.
10. J. W. May, unpublished.
11. M. L. Ott, in *Proc. 19th Annual Meeting of the Adhesion Society*, T. C. Ward, Ed., Adhesion Society, Blacksburg, VA, 1996, pp. 70–73.
12. J. C. Maher, *IS&T's Tenth International Congress on Advances in Non-Impact Printing Technologies*, IS&T, Springfield, VA, 1994, pp. 156–159.
13. E. T. Miskinis, *Proc. Sixth International Congress on Non-Impact Printing*, IS&T, Springfield, VA, 1990, pp. 101–110.
14. D. M. Rakov, unpublished results.
15. J. R. Edinger, Jr., *J. Imag. Sci. Technol.* **36**, 249 (1992).
16. R. P. Dooley and R. Shaw, *J. Imag. Sci.* **5**, 190 (1979).
17. T. A. Jadwin and D. S. Rimai, U.S. Patent 4,517,272 (1985).
18. H. Iimura, H. Kurosu and T. Yamaguchi, *Proc. of IS&T's NIP15: International Conf. on Digital Printing Technologies*, IS&T, Springfield, VA, 1999, pp. 535–538.
19. D. S. Rimai, L. P. DeMejo and R. C. Bowen, *J. Appl. Phys.* **68**, 6234 (1990).
20. D. A. Hays, in *Advances in Particle Adhesion*, D. S. Rimai and L. H. Sharpe, Eds., Gordon and Breach, Amsterdam, 1996, pp. 41–48.
21. K. L. Johnson, K. Kendall and A. D. Roberts, *Proc. Roy. Soc. London, Ser. A* **324**, 301 (1971).
22. E. A. Eklund, W. H. Wayman, L. J. Brillson, and D. A. Hays, in *IS&T's Tenth International Congress on Advances in Non-impact Printing Technologies*, IS&T, Springfield, VA, 1994, pp. 142–146.
23. R. C. Bowen, L. P. DeMejo and D. S. Rimai, *J. Adhesion* **51**, 191 (1995).
24. M. C. Zaretsky, *J. Imag. Sci. Technol.* **37**, 187 (1993).
25. L. B. Schein and G. Beardsley, *J. Imag. Sci. Technol.* **37**, 451 (1993).