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Toner Adhesion: Effects of Electrostatic and van der Waals Interactions

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The force needed to detach spherical toner particles having a number average radius of 7.1 μm from an organic photoconductor was determined by ultracentrifugation. In the absence of any release agents applied to the photoconductor, it was found that only a small fraction of the toner particles could be removed from the photoconductor, even at the highest centrifugal accelerations (354,000 g). However, when the photoconductor was coated with a thin layer of zinc stearate, the release force was reduced substantially and detachment was readily achieved, the remaining release force varying with the square of the toner charge-to-mass ratio. Hence, the residual detachment force varied as the square of the particle charge. These results suggest that electrostatic forces become dominant when van der Waals forces are greatly reduced. Conversely, the large increase in toner adhesion to a photoconductor observed in the absence of a good release agent suggests that van der Waals forces may often dominate toner adhesion for this size particle.

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Introduction

The adhesion of toner particles to photoconductors has been a topic of interest for many years. Moreover, this interest has intensified as the demand for improved image quality has pushed the diameter of toner particles down from approximately 20 μm two decades ago to about 8 μm today. This interest has been driven by the fact that the smaller toner particles are both more difficult to transfer from the photoconductor to a receiver and more difficult to remove during subsequent cleaning operations.[1]

Two mechanisms have been proposed in order to explain the adhesion of toner particles to a photoconductor. The first assumes that the adhesion results from electrostatic interactions between the charged particles and the photoconductor. The second mechanism ignores the role of electrostatic charges and assumes that adhesion forces arise from van der Waals interactions. In reality, as discussed by Gady and co-workers,[2] both types of forces contribute to the attractive forces giving rise to toner adhesion and the real question should be what determines the relative magnitudes of these forces.

Interpretation of the experimental results obtained over the years has been quite contradictory. For example from their measurements of the forces needed to separate Xerox E and K toners, having diameters between approximately 3 and 50 μm, from selenium photoconductors, Goel and Spencer[3] concluded that both electrostatic and surface forces played significant roles in toner adhesion. They also reported that adhesion increased with time. The latter is suggestive of plastic flow arising from the adhesional-induced stresses, as proposed by Krupp[4] and advanced by Maugis and Pollock[5] and by Rimai and co-workers.[6,7]

Hays[8] measured the force needed to detach spherical 13 μm diameter toner particles from magnetic carrier particles often used in so-called "two-component developers", common in electrophotographic engines. Assuming that the charge was uniformly distributed over the toner, he concluded that electrostatic forces could account for only about 1/4 of the total force of adhesion. He also proposed the possibility that nonuniformly charged patches might increase the electrostatic contribution to the total adhesion force. In describing the nonuniform charging, Hays coined the term "charged patch" to describe his model.

Hays and Wayman[9] studied the adhesion forces of 12 μm spherical toner particles using a technique in which the particles were "bounced" between a pair of electrodes. From the results they obtained, they concluded that van der Waals and electrostatic forces contributed approximately equally to the total adhesion force. However, at a later date, Hays and Wayman[10] used similar techniques with 99 μm diameter dielectric particles and concluded that nonuniform charge distributions were the dominant contributor to toner adhesion. It should be noted, of course, that the size of the particles could play a major role. Eklund and co-workers[11] also concluded that nonuniformly charged patches dominate adhesion for 20 μm diameter toners.

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In contrast Mastrangelo[12] used an ultracentrifuge to determine the detachment forces of IBM toner particles having diameters between approximately 6.5 µm and 20 µm from hard and soft photoconductors. He concluded that van der Waals interactions dominated over electrostatic contributions to the adhesion of toner. Moreover, he found that irregularly-shaped toner was less adhesive than spherical toner. Finally, he reported that increasing the toner charge from 1 to 40 esu/cm^2 only increased the separation force from 400 to 650 nN. Similarly, Nebenzahl and co-workers[13] reported only a weak dependence of cleaning efficiency on toner charge for similar toners. These results would seem to argue against the electrostatic charged patch model. [14]

Gady and co-workers[15] took a novel approach to distinguish between the van der Waals and electrostatic contributions to particle adhesion. Instead of measuring the force needed to separate a toner-like particle from a substrate, he measured the attractive force and the attractive force gradients as a function of particle-to-substrate separation by attaching spherical polystyrene particles between approximately 6 µm and 12 µm to an atomic force microscope (AFM) cantilever. Then, by comparing the power-law dependence of the force and force gradient with the theoretical dependences, they concluded that the van der Waals forces become more dominant at separation distances less than approximately 10 nm. However, there was an observable increase in the attractive and separation forces with the number of times the particle was allowed to contact a triboelectrically dissimilar substrate. Moreover, subsequent washing the particle with methanol decreased these forces, suggesting that localized charged patches can play a role in determining the separation forces.

On the other hand Donald[16] determined that electrostatic forces dominate the adhesion of a variety of beads approximately 1/2 mm in diameter. Donald and Watson[17] used an ultracentrifuge to detach toner from carrier. They then measured the charge on the detached toner as a function of centrifuge speed and concluded that the toner to carrier adhesion was dominated by electrostatic forces.

Using 20 µm diameter toner, Lee and Jaffe[18] also determined toner to photoconductor and toner to carrier separation forces. The former force was determined using an ultracentrifuge, whereas the latter was determined using an air-jet and assuming that the air impinging on a carrier is proportional to the applied air pressure. They further argued that, although the measured forces seemed to agree with the values predicted assuming the dominance of van der Waals interactions, such a model could not possibly be correct for two reasons. First, the van der Waals force model overestimates the force of attraction because of the irregular shape of toner and second, electrostatically charged patches actually cause the electrostatic forces to be substantially larger than one would estimate assuming a spherical particle. It should be noted that this same article shows scanning electron micrographs of toner particles in contact with the photoconductor. These particles appear to be relatively smooth, although irregular, in shape and seem to be resting on flat surfaces of the particles. As discussed by Bowling[19] in the same reference, such a contact would actually increase the effect of van der Waals forces.

In a recent study Iimura and co-workers[20] reported the effects of surface treatment on toner adhesion. They concluded that, although the effect of van der Waals forces was measurable, the dominant force of adhesion was due to electrostatically charged patches.

In contrast to Iimura, Gady and co-workers[21] studied the effects of silica concentration on toner adhesion, cohesion, transfer, and image quality using 8.6 µm ground toners. They concluded that van der Waals interactions dominated the adhesion forces for silica concentrations less than about 2% by weight. When the silica concentration reached 2%, the van der Waals and electrostatic forces were comparable. They further argued that the magnitude of the electric fields achievable in air without breakdown limits the forces that one can realistically obtain from either localized charged patches or from uniform charge distributions to the range of 20 – 40 nN.

In yet another study Rimai and co-workers[22] used electrostatic detachment to determine the force needed to separate monodisperse spherical toner particles from a photoconductor. For particles with diameters between 2 and 12 µm, they reported that the van der Waals interactions appear to be much greater than the electrostatic contributions to adhesion.

There are a number of reasons for the apparent discrepancies in the findings of so many researchers. First, of course, is the issue of the size of the toner. In is unrealistic to expect toner particles having diameters between 50 and 100 µm to have the same dominate forces as those having diameters that are smaller than 10 µm. The fact that electron charges are primarily resident on the surfaces of particles, while the time-dependent electron distribution responsible for van der Waals interactions are distributed throughout the particles will naturally lead to differences in the particle size-dependence of the force laws associated with the two phenomena. Thus, it is natural to expect a change in the dominant mechanism with a change in the size of the particles. Second, the irregular shape of ground toner particles and the presence of submicrometer particulate addenda such as silica greatly complicate analysis. Irregular particles have a spectrum of local radii of curvature at the points where they interact with surfaces and, thus, should exhibit a range of apparent behaviors even for a fixed mechanism. Finally, certain of the assumptions commonly made to analyze toner adhesion need to be questioned For example the effect of the induced image charge of neighboring particles is often neglected. However, as discussed by Goel and Spencer,[3] charged particles can see the image charge associated with the presence of neighboring particles and, in the case of an hexagonally close-packed monolayer, the effect of the additional image charges would be to increase the electrostatic component by a factor of 6.95. In order to more fully understand the relative roles of the toner charge and van der Waals interactions, this article reports measurements of the forces needed to detach spherical toner particles from an organic photoconductor as a function of toner charge.

Experimental

The force needed to detach spherical toner particles, having a number-averaged diameter of 7.1 µm, from an organic photoconductor was measured using ultracentrifugation.

The toner particles were made from a commercially available polyester binder having a mass density of 1.2 g/cm^3, using the limited coalescence process, as described elsewhere.[2] The toner particles produced in this manner were highly monodisperse and spherical. Toner size was determined using a Coulter Multisizer. Twelve

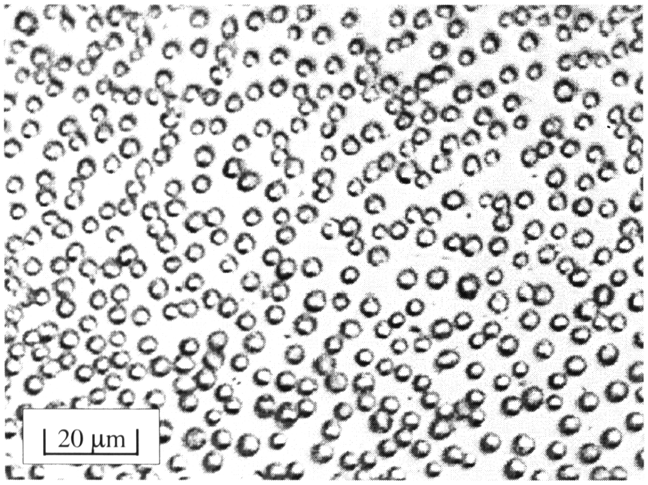


Figure 1. A photomicrograph of the toner deposited on the photoconductor.

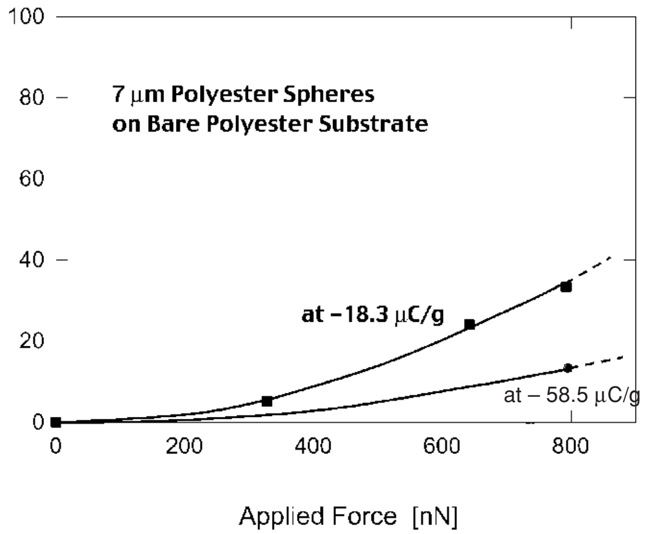


Figure 2. The percent of toner removed from a bare (no zinc stearate) photoconductor as a function of the applied detachment force for q/m = 18.3 (2a) and 58.5 (2b) μC/g.

grams of developer were prepared by mixing 0.6 g of toner with 11.4 g of magnetic carrier, which served to negatively charge the toner particles, in a small vial. No third component addenda were included. After agitating and, thus, tribocharging the contents of the vial using a paint mixer, the charge-to-mass ratio of the toner was determined using the method of Maher,[23] as discussed by Gady and co-workers.[21] The developer was then placed on the roller of a sumpless SPD development station, described by Miskinis.[24]

The toner was deposited onto a new, commercially available organic photoconductor comprising a polyester binder by grounding the conductive layer of the photoconductor and adjusting the bias on the development station until a random deposition of toner covering between 30 and 40% of the photoconductor was obtained. A photomicrograph of the toner deposited in this manner is shown in Fig. 1. It should be noted that a random deposition of toner does not mean that the toner is uniformly deposited. Rather, according to calculations by Zeman,[25] a random deposition of toner particles would result in the formation of toner chains, with linear arrays of toner particles in close proximity to one another, similar in form to a string of pearls, or pearl chain. That is, a truly random arrangement appears to contain chain-like structures. Such arrays are apparent in Fig. 1. The significance of this will be discussed later in this article. Initially, the toner was deposited onto a new, untreated photoconductor. However, it was found that few of the toner particles could be removed from this photoconductor, even for the lowest charged toner particles and the highest centripetal accelerations. Consequently, and for the majority of the results reported herein, the photoconductor was coated with a monolayer of zinc stearate prior to toner deposition. Zinc stearate is a known and highly effective release agent for toner.[22,26–28]

The detachment force of the toner from the photoconductor was determined using a Beckman L8-70M ultracentrifuge capable of speeds of 70,000 rpm. The samples were placed in a rotor with a radius of 6.45 cm. The number of particles on the photoconductor was counted both initially and after spinning at a chosen speed under a microscope, using Image-Pro particle counting software. In order to minimize effects associated with increases in adhesion measured with time, as previously reported in the literature,[13,29] all samples were run in the centrifuge on the same day that the toner was deposited on the photoconductor. In addition data points at different speeds were determined by two methods. The first method consisted of generating the general curve of the percent detached as a function of the centrifuge speed by simply increasing the speed to which a given sample was subjected. Next, additional data points were obtained by running the centrifuge at different speeds selected randomly. The data obtained from these two methods were found to be indistinguishable and are presented in the figure contained herein. The force needed to detach the toner particles from the photoconductor was considered to be the centrifugal force applied when 50% of the toner separated from the photoconductor.

Results

The detachment force F_{detach} exerted on a particle is related to the mass m of the particle, the angular frequency ω, and the radius R of the rotor by

$$F_{detach} = m\,\omega^2 R. \tag{1}$$

Because the particles were both monodisperse and spherical, the mass of each particle was readily calculated and found to be 2.34×10^{-10} g. For particles with this mass, the maximum detachment force that can be exerted with this centrifuge is approximately 811 nN.

Figure 2 shows the percent removed from the photoconductor as a function of the centrifugal force for charge-to-mass ratios of 18.3 and 58.5 μC/g, from a bare photoconductor that had not been coated with zinc stearate. It is evident from this figure that, at maximum centrifuge speed, the centrifugal force was unable to remove the toner particles from the photoconductor. That is, substantially less than 50% of the toner particles could be removed for even these lowest values of the charge-to-mass ratio. This precludes the ability to determine the detachment forces as a function of charge-to-mass under these conditions. There does appear to be a decrease in the amount of toner removed from the photoconductor with increasing q/m ratio. This is not surprising as, even if van der Waals forces are dominant in determining toner adhesion, electrostatic forces would still contribute to the total force of adhesion.

The inability to detach the toner particles is, perhaps, not surprising if one simply estimates the force that one needs to apply to each particle to accomplish this. This is readily accomplished using JKR theory,[30] as discussed elsewhere.[21,22] Accordingly, the force needed to effect detachment, ignoring, for the time being, electrostatic contributions to the attractive force, is given by

$$F_{detach} = -\frac{3}{2}\pi w_A R \tag{2}$$

where w_A is the work of adhesion. The work of adhesion is related to the surface energies of the toner and photoconductor γ_T and γ_{Ph} and their interfacial energy γ_{T-P} by

$$w_A = \gamma_T + \gamma_{Ph} - \gamma_{T-P}. \tag{3}$$

The surface energies of the toner and photoconductor materials, as determined from the contact angles with distilled water and diiodomethane, were between 0.040 and 0.045 J/m^2. This is in good agreement with literature values. The interfacial energy is more difficult to determine. However, because both materials are similar, γ_{T-P} should be relatively small, as the interfacial energy between identical materials is zero. If one allows a small, but finite, value for the interfacial energy, one finds that a reasonable estimate of the work of adhesion is approximately 0.070 J/m^2. Accordingly, one would estimate the detachment force to be approximately 1100 – 1200 nN. This, of course, neglects contributions to the attractive forces due to the presence of any electrostatic charges, which should further increase the detachment force These results and estimates are in reasonable agreement with experimentally determined 1,100 nN detachment forces for 8.6 µm ground toner without silica, reported by Gady and co-workers.[21] However, they disagree with the experimental results of Iimura and co-workers,[20] who reported that the detachment force for comparable size, uncharged toner particles, without silica, to be approximately 70 nN. It is recognized that the consistency between the detachment forces predicted assuming van der Waals interactions and the present measurements are not sufficient to prove the dominance of these forces. However, these results, taken together with an extensive body of literature, should be sufficient to at least argue that van der Waals forces cannot simply be discounted at this time. Most notably, the linear dependence of the detachment force on toner radius[22] is consistent with the JKR theory assuming the dominance of van der Waals forces.

In order to experimentally determine the contribution of the electrostatic forces to toner adhesion, it is necessary to be able to remove most of the toner, in a quantifiable manner, from the photoconductor. Then, by extrapolating the detachment force as a function of toner charge to the case where $q/m = 0$, one can determine both the surface force and electrostatic contributions to toner adhesion can be determined. This could not be done using the photoconductor as is because it was only possible to remove small amounts of the toner.

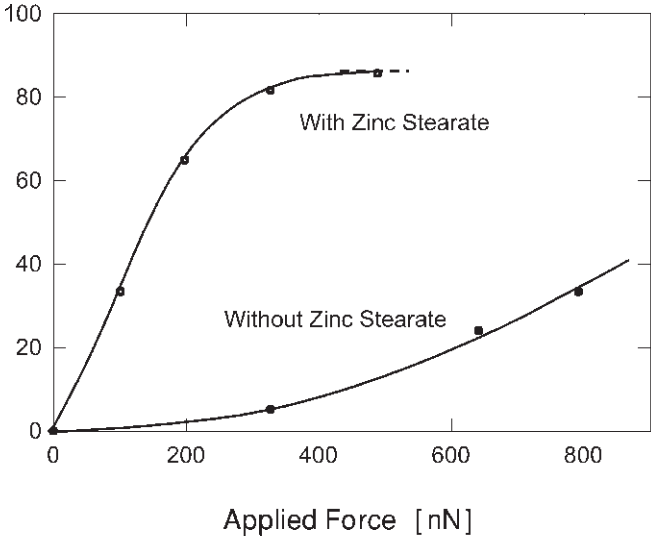
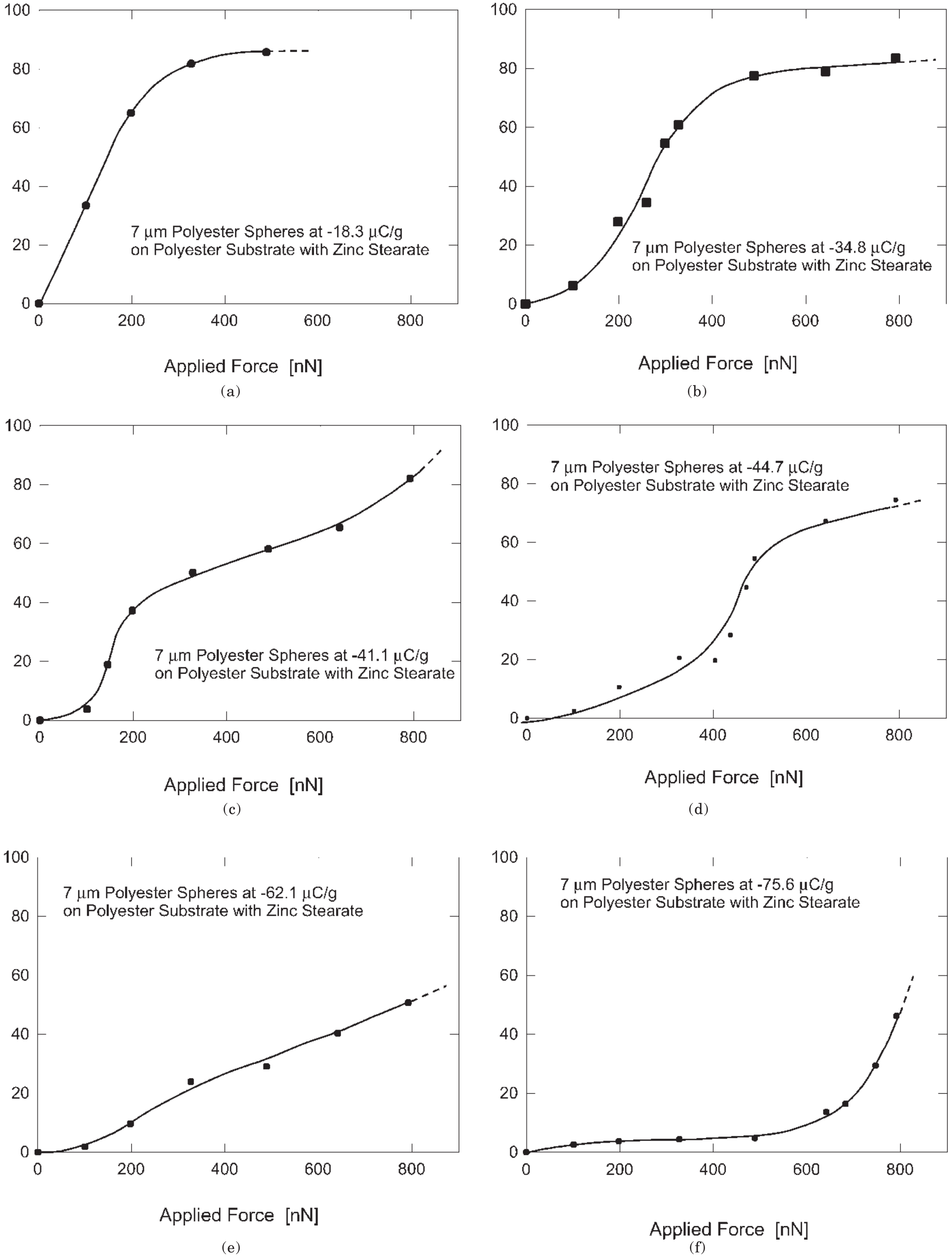


Figure 3. Comparison of the percent removed as a function of the applied force with and without zinc stearate on the photoconductor.

If one assumes that surface forces, such as those attributed to van der Waals interactions, dominate adhesion, it should be possible to reduce those using known release aids such as zinc stearate or Teflon coatings on the photoconductor. Conversely, if the application of such a release agent does not significantly alter the amount of toner removed, one could argue that the dominant adhesive interaction is electrostatic in nature. Assuming that the release agent does not affect toner charge, the electrostatic contribution to adhesion should be the same whether or not the photoconductor is overcoated with the release agent. It should be noted that, if the toner charge is significantly altered by the presence of zinc stearate, the toner lay down at constant development station potential and the potential on the photoconductor after development should also be altered. Neither effect was observed in this study. In this study zinc stearate was chosen as the release agent because it has previously been found to show the greatest reduction in toner adhesion.[22] Figure 3 shows the efficiency with which zinc stearate can increase the percentage of toner removed removed at the same applied force and charge-to-mass ratio. Although the thickness of this layer was not determined in the present instance, previous ESCA studies suggest the thickness of the zinc stearate coating is approximately 4 nm, when similar means of deposition were employed. In previous studies[22] zinc stearate was found to significantly reduce the adhesion of positively charged toner to similar photoconductors. In this case, the toners are negatively charged, arguing that the role of the zinc stearate is effective in reducing adhesion, rather than altering the charges present. From the measured potentials on both the untreated and zinc stearate coated photoconductors after development and the initial particle counts on the photoconductor prior to centrifugation, it would appear that, in this instance, the presence of zinc stearate did not appreciably alter the toner charge. A direct comparison of q/m, as measured by capturing the toner in a Faraday cage, of the toner particles on both the zinc stearate coated and uncoated photoconductors would be desirable. Unfortunately, it was not possible to remove the toner from the uncoated photoconductor in a way that would allow q/m to be determined. Figures 4a through 4f show the percent of toner removed at different centrifugal forces for toner with charge-to-



(a) (b) (c) (d) (e) (f)

Figure 4. The percent of toner with charges of (a) –18.3, (b) –34.8, (c) –41.1, (d) –44.7, (e) –62.1 and (f) –75.6 µC/g removed from zinc stearate overcoated photoconductor as a function of the applied centrifugal force.

mass ratios of –18.3, –34.8, –41.1, –44.7, –62.1, and –75.6 μC/g, respectively. Typically, toners of this approximate size, when used in electrophotographic engines, have charge-to-mass ratios of approximately 35 μC/g. As can be seen from these figures, there tends to be a sharp transition from a situation where little toner is removed to one where most of the toner is removed. This is in distinct contrast to the case without the application of the zinc stearate, where little toner was removed even at the highest applied forces. Moreover, the force needed to detach the toner appears to increase monotonically with increasing q/m.

The fact that the force needed to detach a toner particle from a photoconductor increases with toner charge has been clearly established in both this and aforementioned referenced works. The two questions that remain are 1) what are the relative contributions to toner adhesion from the van der Waals versus the electrostatic interactions and 2) by what mechanisms do electrostatics contribute to toner adhesion. Let us consider the second question first.

As is well known, a uniformly charged particle in contact with a grounded conducting substrate will induce an electrostatic image charge so that the net force of attraction F_I is given by

$$F_I = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{(2R)^2} \tag{4}$$

where q is the charge on the particle and e_0 is the permittivity of free space As discussed by Hays,[14] Eq. 4 can be generalized to include polarizable materials by multiplying the right hand by some constant a. However, when the dielectric constants of the contacting materials are equal, as would be the present case, $a = 1$.

Alternatively, the electrostatic charge need not be distributed uniformly over the entire surface of the particle. Rather, it can be localized to certain areas often referred to as charged patches. According to this model,[14] the charge of the toner is related to the total area of the toner A_t by

$$q = \sigma A \tag{5}$$

where σ is the surface charge density. If the extent of the charged area of the toner particle A_c in contact with the photoconductor is large compared to the separation distance between them, then the electrostatic attractive force F_E is given by the particle-substrate contact could be treated as a parallel plate capacitor and

$$F_E = \frac{\sigma^2 A_C}{2\varepsilon_0}. \tag{6}$$

If, indeed, the charge varies linearly with the charge density, as would be the case where the charge density were constant, then F_E would also vary as the square of the toner charge. It should be noted, however, that equations 4 and 5 are generally not consistent with the fundamental assumptions of the charged patch model. Rather, q would be a function of position on the particle surface and would not simply be proportional to the area of the toner. Moreover, σ would not be constant. The total charge would be given by

$$q = \oiint \sigma(r,\theta,\varphi)\,dA(r,\theta,\varphi), \tag{7}$$

which, in most cases, would not simply reduce to Eq. 5. Similarly, Eq. 5 is derived from the parallel plate capacitor approximation and also assumes a constant charge density. Moreover, Eq. 6 also assumes that the contribution to the attractive force by any charge located outside the contact region is negligible. However, within the approximations commonly used in the charged patch model, one would expect the attractive force to also vary as the square of the toner charge.

Another proposed contribution to the electrostatic component of the attractive force comes from polarization effects, as proposed by Fowlkes and Robinson.[31] According to this model, a charged dielectric particle in contact with a conducting substrate would induce an electrostatic image charge. That image charge would then induce a dipole in the particle. The dipole would then induce image charges in the substrate, that correspond to a quadrupole. The quadrupole would induce an octopole in the particle. This process would go on *ad infinitum*, thereby generating an infinite series. As each contribution adds to the attractive force, this series would only slowly converge. In this instance the attractive force would not be expected to vary simply as the square of the particle charge.

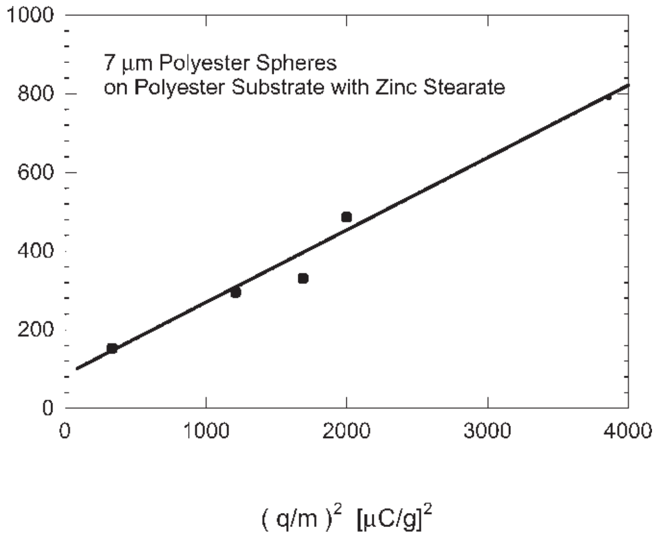


Figure 5. The applied force needed to detach 50% of the toner from zinc stearate coated photoconductors as a function of $(q/m)^2$.

Figure 5 shows a plot of the force needed to detach half the particles from the zinc stearate coated photoconductor as a function of the toner charge-to-mass ratio. (The reader should note that q/m, rather than simply q, was plotted, as this was the actual measured quantity. However, the same toner was used throughout this study, with the charge varied by changing the type of carrier. The charge can be estimated by multiplying q/m by the calculated toner mass per particle = 2.34×10^{-10} g).

As is apparent from Fig. 5, the detachment force appears to vary linearly with $(q/m)^2$, as would be predicted by the simple uniformly charged particle model and may be predicted by the charged patch model. However, in light of the simple dependence of the detachment force on q/m and the magnitude of the detachment force, it appears unlikely that multipole moments contribute significantly to the attractive forces.

The reasons for being able to exclude the multipole model are fairly straight forward. The multipoles (aside from the monopole moment, which is simply the charge) all depend on the differences between the dielectric constants of the particle and substrate and the surrounding media (i.e., air). However, when the particle is in contact with the substrate, there is no intervening medium. In that case the multipoles would depend on the difference between the dielectric constants of the two materials. For toners and organic photoconductors, this difference, to a high degree of approximation, is zero. Outside the immediate contact, the multipoles would depend on the difference between the dielectric constants of the particle and photoconductor and the intervening air. However, the contributions of the multipoles to the attractive forces decrease very quickly with separation distances, resulting in only small contributions to the attractive forces.

Let us now consider the effects of the charge on the attractive force. To quantify this, it is first necessary to eliminate contributions to adhesion from the van der Waals interactions. This can be approximated by extrapolating the straight line in Fig. 5 to the value $q/m = 0$. Upon doing so it is found that there is a residual force of approximately 100 nN, which is much smaller than the force of adhesion observed for the bare photoconductor. Evidently, the presence of zinc stearate greatly reduced the van der Waals forces, that is, the attractive forces when $q/m = 0$. This value is in good agreement with van der Waals contribution reported by Iimura and coworkers[20] for comparable size toner particles without silica coatings. The electrostatic contribution to the attractive force for a uniformly charged isolated sphere can be calculated using Eq. 3. Let us consider, for example, the case where $q/m = 18.3$ μC/g. The total force needed to detach the particles was found to be approximately 180 nN. The electrostatic contribution to the attractive force was calculated to be 40 nN, for a total force of 140 nN. However, as discussed earlier in this article, the random deposition of toner particles results in the particles forming "pearl chains". Each neighboring particle also creates its own image charge, which interacts with every other charged particle in the system. If we simply add to the attraction from the primary image charge, the attraction due to the image charge of the two neighboring particles, we find that the total attraction is twice that experienced by an isolated particle. In this case the electrostatic attraction would then be 80 nN, rather than 40, for a total attractive force of 180 nN. This is in good agreement with the measured detachment force. For a more typical case, where the charge is approximately twice that of the example just cited, the total electrostatic attraction, including the effect of the two nearest neighbors, would be four times as large as the cited example, or 160 nN. The total attractive force would be approximately 260 nN. For toners with this charge, the detachment force was measured to be approximately 270 nN. Similar agreement is found with other charge-to-mass ratios. These values appear to be in reasonable agreement with reported measurements of Iimura and co-workers.[20] A further test of this hypothesis would be to determine the electrostatic contribution to the toner adhesion as a function of toner lay down, at constant charge.

At this point let us revisit the apparent effect of q/m on the adhesion of the toner to the photoconductor without the zinc stearate. If one assumes that the presence of zinc stearate did not affect the toner charge or charge distribution, which is discussed earlier in this article, one can use the data presented in Figure 5 to estimate the contribution arising from the toner charge to the total force of adhesion. Accordingly, if $q/m = -58.5$ μC/g, the total charge holding the toner to the photoconductor would be approximately 700 nN per particle. Subtracting approximately 100 nN attributed to nonelectrostatic interactions for the zinc stearate coated photoconductor gives a contribution to the force of adhesion of approximately 600 nN. The total force of adhesion of this toner from the uncoated photoconductor can be approximated by the sum of the electrostatic and nonelectrostatic contributions, for a total of 1,700 to 1,800 nN. Similarly, if $q/m = 18.3$ μC/g, the force of adhesion from the zinc stearate coated photoconductor would be approximately 340 nN. Again, subtracting approximately 100 nN would give an increment to the total adhesion force of approximately 240 nN, for a total estimated to be between 1,340 nN and 1,440 nN. Thus, even if van der Waals interactions dominate the adhesion of toner particles of this size to photoconductors that have not been coated with a release agent, there still should be an observable contribution to the total force of adhesion due to electrostatic effects.

Conclusions

The force needed to detach monodisperse, spherical toner particles having a diameter of approximately 7.1 μm from an organic photoconductor was measured using ultracentrifugation. The force needed to remove that toner from a bare photoconductor was found to exceed 800 nN. Using JKR theory, the detachment force was estimated to be approximately 1100 nN for this case. In contrast, upon application of a thin layer of zinc stearate onto the photoconductor, the van der Waals forces were reduced to approximately 100 nN. The detachment force was then found to vary as the square of the toner charge. For an isolated toner of this size with a typical charge-to-mass ratio of about 36 μC/g, the electrostatic contribution was estimated to be approximately 80 nN. The calculated value, however, is estimated to double if one includes the image charges associated with two adjacent particles found in the observed pearl-chain-like structures of the randomly-deposited toner. Unless the van der Waals forces are deliberately and significantly reduced through the use of release agents such as zinc stearate, they appear to be the dominant interactions controlling toner adhesion, with electrostatic contributions being at least an order of magnitude smaller. However, by using suitable release agents, the van der Waals forces can be reduced to the point where they account for less than half of the toner adhesion, depending upon the charge of the toner.

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