The Adhesion of Spherical Toner: Electrostatic and van der Waals Interactions

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Abstract

The force needed to remove spherical toner particles having a number average radius of 7.1 µm from an organic photoconductor was determined by ultracentrifugation. It was found that only a small fraction of the toner particles could be removed from the photoconductor, even at the highest centrifugal accelerations (354,000g) from the bare photoconductor. However, when the photoconductor was coated with a thin layer of zinc stearate, toner removal was readily achieved. It was found that the release force from the zinc stearate-coated photoconductor varied with the square of the toner charge-to-mass ratio. These results suggest that, while both van der Waals and electrostatic forces contribute to the adhesive interaction between toner particle and photoconductors, the van der Waals forces dominate for this size particle in the absence of release agents. Conversely, in the presence of good release agents, van der Waals forces can be reduced to a level where they are comparable or smaller than electrostatic interactions.

Introduction

Interest in the adhesion of toner particles to photoconductors 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 triggered by the increased difficulty in transferring the toned images and cleaning the photoconductor encountered with the decease in toner size.[1]

Two types of forces have been proposed to explain the adhesion of toner to a photoconductor. The first assumes that the adhesion results from electrostatic interactions.. The second assumes that adhesion forces arise from van der Waals interactions. In reality, as discussed by Gady *et al.*,[2] both types of forces contribute to toner adhesion. The actual question that should be asked is what are the relative magnitudes of these forces.

Interpretation of the experimental results obtained over the years has been quite contradictory. For example, Goel and Spencer[3] concluded that both electrostatic and surface forces played significant roles in toner adhesion. Moreover, they found that adhesion increased with time, suggestive of the occurrence of plastic deformations, as proposed by Krupp[4] and advanced by Maugis and Pollock[5] and by Rimai *et al.*[6,7]

Hays[8] measured the force needed to detach spherical 13 µm-diameter toner particles from magnetic carrier particles. Assuming that the charge was uniformly distributed over the toner, he concluded that electrostatic forces could account for only about ¼ of the total force of adhesion. He also proposed that nonuniformly charged patches might increase the electrostatic contribution to the total adhesion force.

Hays and Wayman[9] studied toner adhesion using a technique in which the particles were “bounced” between a pair of electrodes. They concluded that van der Waals and electrostatic forces contributed approximately equally to the total adhesion force. Subsequently, Hays and Wayman[10] concluded that the adhesion of 99 µm diameter dielectric particles was dominated by nonuniform charge distributions. It should be noted, of course, that the size of the particles would be expected to greatly affect the mechanism. Eklund *et al.*[11] also concluded that nonuniformly charged patches dominate adhesion for 20 µm diameter toners.

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. This would appear to contradict the charged-patch model, in which the presence of the asperities should further enhance the localization of the charge and, thus, its contribution to adhesion. 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. Nebenzahl *et al*.[13] also reported a weak dependence of cleaning efficiency on toner charge. These results seemingly contradict the electrostatic charged patch model.[14]

Gady *et al.*[15] 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. 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. In addition they found that washing the particle with methanol decreased these forces, suggesting that localized charged patches can play a role in determining the separation forces.

Donald[16] reported that electrostatic forces dominate the adhesion of a variety of ½ mm diameter beads. Donald and Watson[17] used an ultracentrifuge to detach toner from carrier. They concluded that the toner-to-carrier adhesion was dominated by electrostatic forces.

Using 20 µm diameter toner, Lee and Jaffe[18] measured the detachment force of 20 µm diameter toner to a photoconductor and toner to carrier. They found that the measured detachment forces were consistent with estimates made assuming van der Waals interactions. However, they argued that this model could not possibly be correct for two reasons. First, the van der Waals force model would overestimate 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. The toner 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] such a contact would actually increase the effect of van der Waals forces.

Iimura *et al*.[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.

Gady *et al*.[21] also measured 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 limits the obtainable adhesion forces due to either localized charged patches or from uniform charge distributions to 20 – 40 nN.

Rimai *et al*.[22] used electrostatic detachment to determine the force needed to separate monodisperse spherical toner particles, having diameters between 2 and 12 µm, from a photoconductor. They concluded 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 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. Second, the irregular shape of ground toner particles and the presence of submicrometer particulate addenda such as silica greatly complicates 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, many of the assumptions commonly made to analyze toner adhesion are fundamentally flawed and lead to improper conclusions. However, since these conclusions appear to explain the data, alternative mechanisms are often ignored. For example the effect of the induced image charge of neighboring particles is commonly neglected when calculating the electrostatic contribution to toner adhesion.

In order to more fully understand the relative roles of the toner charge and van der Waals interactions, this paper reports measurements of the forces needed to detach spherical toner particles from an organic photoconductor as a function of toner charge.

Experiment

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, comprising a polyester binder with a density of 1.2 g/cm^3, were made using the limited coalescence process.[2] These particles produced in this manner were highly monodisperse and spherical. Toner size was determined using a Coulter Multisizer. Twelve grams of developer were prepared by mixing 0.6 g of toner with 11.4 g of carrier, which served to negatively charge the toner particles. No third component addenda were included. After agitating with a paint mixer, the charge-to-mass ratio of the toner was determined using the method of Maher,[23] as discussed by Gady *et al*.[21] The developer was then placed on the roller of a sumpless SPD development station, described by Miskinis.[24]

The toner was deposited onto an organic photoconductor 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. 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 similar in form to pearl chains. The importance of this will be discussed later in this paper. At first the toner was deposited onto a new, untreated photoconductor. However, it was found that only a few of the toner particles could be removed from this photoconductor, even for the lowest charged toner particles at 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 force needed to remove 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 determined 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 over time, as previously reported in the literature,[13,29] all samples were run 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. Second, additional data points were obtained by running the centrifuge at different speeds selected randomly. 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 and Conclusion

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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Biography

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