Theory of Electric Field Detachment of Charged Toner Particles in Electrophotography

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In the electrophotographic process, electric fields are used to detach and move charged toner particles from one surface to another. In principle, electric field detachment occurs when the applied electrostatic force overcomes the toner adhesion force to a surface. For triboelectrically charged toner, many measurements have indicated that the electrostatic adhesion force is much greater than that calculated for a uniformly charged dielectric sphere, suggesting that the surface charge distribution on a toner particle is nonuniform. In the present work, the physics of the electrostatic force is described and a dumb-bell type charge distribution on triboelectrically charged toner particles is proposed as an approximation of nonuniformly charged particles. The electrostatic force on an isolated toner particle with a dumb-bell type charge distribution is computed by means of a recently developed computational method based on a Galerkin finite-element technique. The effect of the electrode spacing on the electric field detachment of charged toner particles is examined in particular. The results show that the magnitude of electrostatic force is rather insensitive to the electrode spacing when the particle is nonuniformly charged, unless the spacing is so small that the counter electrode is nearly touching the particle. The electrostatic force for detaching a charged particle is shown to become maximized when the particle charge and applied field strength satisfy a certain relationship. Formulas are also derived for the minimum electric field strength and the corresponding particle charge that are required for the maximized electrostatic detaching force to overcome the non-electrostatic components of adhesion. For triboelectrically charged toner particles, the components of the electrostatic force components are shown to be much greater than non-electrostatic force components. If the particle charge is proportional to the particle surface area and the non-electrostatic force component is relatively insignificant, the detachment of toner particles in response to an applied electric field should be independent of the particle size.

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Introduction

The invention of electrophotography (often also referred to as xerography) by Chester Carlson in 1938 is based on the physical fact that charged particles can be moved by an externally applied electric field.[1] A simplified sketch of a typical electrophotographic process for copying and printing is shown in Fig. 1. Toner particles used in electrophotography are typically about 10 µm in diameter and consist of a pigment dispersed in a polymer resin. The electrically insulating toner particles are usually charged by the phenomenon of triboelectricity,[1–5] as conveniently achieved in the two-component developer charging process. When the developer is brought into close proximity to an electrostatic latent image on a photoreceptor, the charged toner particles deposit on the photoreceptor according to the Coulomb force associated with the latent image. The developed visible image due to toner deposition on the photoreceptor is subsequently transferred to paper by an applied electric field to produce the printed document. The configurations for electric field detachment of toner in an electrophotographic system may vary considerably. For example, in some development systems the toner particles move across a relatively large gap between a toned donor surface and a receiver such as a photoreceptor. Another configuration is encountered when toner is transferred from a photoreceptor to paper or an intermediate material, where the toner particles provide a self-spacing between the donor and receiver to form a small-gap. Regardless of the specific configuration, the basic physical principles involved in electric field detachment of charged toner particles remain the same.

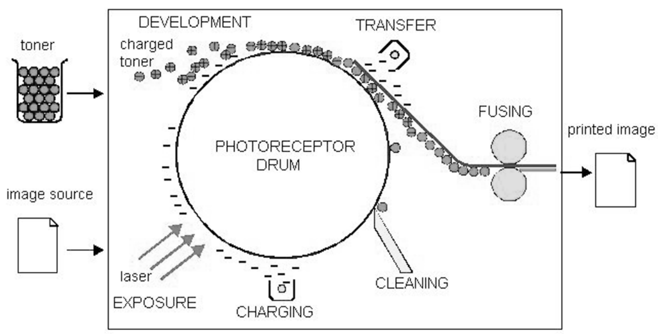

Figure 1. A typical electrophotographic process: Charging the photoreceptor uniformly in the dark; Exposure of photoreceptor to light to create charge pattern called electrostatic latent image; Development with charged toner particles attaching onto the image area on photoreceptor; Transfer of developed toner from photoreceptor to paper; Fixing the image on paper by fusing.

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When a particle contacts a surface, adhesion forces due to several mechanisms come into play.[6] For example, the interaction among instantaneous dipoles in atoms by virtue of fluctuations of electron distributions gives rise to van der Waals forces that attract the particle to the surface. Local transfer of electrons or ions as driven by the difference in work functions between two contacting materials generates double-layer attractive forces. Sharing of electrons between atoms at contacting boundary forms covalent bonds and subsequently introduces chemical forces. If the humidity is high, water vapor may condense in the gap of the contacting area and the resulting capillary forces also contribute to adhesion. If a particle with a substantial amount of electric charge is in contact with a surface, the image charge induced in the substrate material gives rise to an electrostatic adhesion force. In electrophotography, the charge on toner particles is necessary for generating the electrostatic driving force in externally applied electric fields to move toner particles to the desired locations. To enable the functionality of electrophotographic processes, toner particles are formulated and manufactured in such a way to ensure that the electrostatic driving force is dominant over the combination of the short-range adhesion forces and the electrostatic adhesion force. Many experimental measurements and related analyses suggested that the adhesion is dominated by the electrostatic adhesion force due to nonuniform distribution of charge on toner particles.[7,8]

In view of its importance in electrophotography, the calculation of the electrostatic force on toner particles in contact with a material surface has been carried out by many authors for various cases.[6,9–12] Most of those calculations were restricted to cases involving one sphere in contact with a planar surface so as to make the problem tractable when using bispherical coordinates or multipole expansion methods. If the charge is assumed to be uniformly distributed on the dielectric sphere surface, the calculated electrostatic adhesion force on the sphere resting on a conductive plane is found to be much less than the measured values for triboelectrically charged toner.[7,8,11–17] This fact led to the concept of nonuniform charge distribution on triboelectrically charged toner particle surface.[7,8,11,12,15–17,19] Many experimental results, such as measurements of a charged particle bouncing between two plates,[11] seem to be consistent with the assumption of a dumb-bell type charge distribution on toner particles.

In the present work, we begin with describing the physics of the electrostatic force acting on a toner particle and discussing physical mechanisms for the formation of a dumb-bell type charge distribution on a triboelectrically charged toner particle. Then, we compute the electrostatic force for the dumb-bell charge distribution on an isolated dielectric sphere by means of a recently developed computational method based on a Galerkin finite-element technique.[18,19] The effect of the spacing between electrodes on the electric field detachment of charged toner particles is examined in particular. Finally, we discuss the theoretical implication of electric field detachment of toner particles and identify the most important parameters.

Electrostatic Force on a Charged Spherical Particle

The toner commonly used in electrophotographic machines consists of particles that are irregular in shape, since the particles are usually formed by a grinding process. The difficulty in a theoretical calculation of forces on toner arises from selecting a representative shape for irregularly-shaped particles. Although specifying any particular shape may suffer from criticisms as not exactly describing a realistic toner particle, a sphere is the most commonly used shape in theoretical analyses. Not only does a spherical particle become amenable to mathematical solutions by various methods, but it also makes sense either from statistical point of view when simple averaging is performed over a large number of irregularly-shaped particles or from mathematical point of view when shape irregularity is treated as a perturbation from the spherical base shape. Moreover, realistic spherical toner particles have been produced recently through chemical toner techniques.

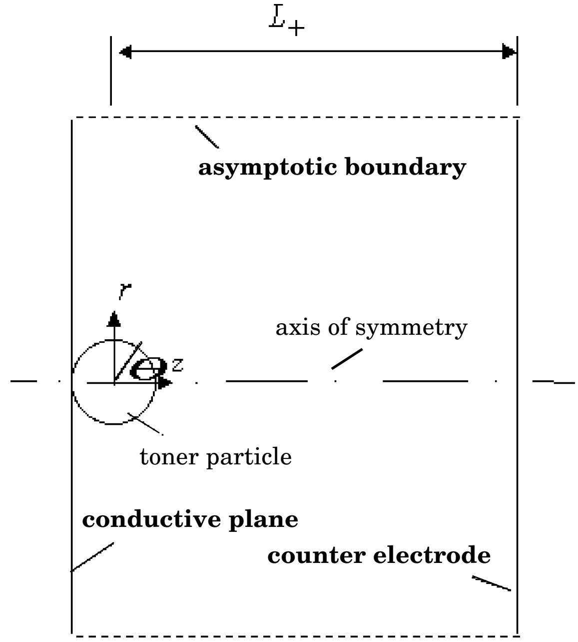

Figure 2. Definition sketch of a toner particle resting on one of the electrodes in a parallel-plate capacitor.

The problem considered here consists of a dielectric toner particle of spherical shape with radius R and net charge Q resting on an electrode of a parallel-plate capacitor (as shown in Fig. 2). This is a generic configuration for electric field detachment in the electrophotographic process. When an electric field of strength E is applied to move the charged toner particle from its residing surface to the other electrode, several components of electrostatic force are generated. The electrostatic adhesion force arises mainly from the attraction between the net charge on the particle and consequent image charges induced on the other side of the material surface on which the particle resides. The interaction between the net particle charge and externally applied electric field gives rise to the electrostatic driving force, or the Coulomb force, which tends to move the particle away from the residing surface. Moreover, the attraction between the induced dipole by the applied electric field and its image dipole on the other side of the particle residing surface also contributes to the electrostatic adhesion, although it may rather be weak in the case of charged toner particles.

In general, the electrostatic force on a charged toner particle in an applied electric field can be written in a dimensionless form consisting of three components as[18,19]

$$F_E = -\alpha\,\sigma^2 + 4\,\beta\,\sigma - \gamma, \quad (1)$$

where the dimensionless global surface charge density is defined as

$$\sigma = Q/(4\,\pi\,\varepsilon_0\,R^2\,E), \quad (2)$$

and the electrostatic force F_E is made dimensionless when measured in units of $(\pi\varepsilon_0 R^2 E^2)$ where ε_0 is the permittivity of the medium surrounding the particle, i.e., air. On the right side of Eq. 1, the first term represents the electrostatic adhesion force due to the attraction between the net charge on the particle and its image charge in the substrate material, the second term stands for the electrostatic driving force or the Coulomb force, and the third term is the electrostatic adhesion force arising from the attraction between the induced dipole in an uncharged dielectric particle in an applied electric field and its dipole image in the substrate material. In contrast to the dimensional form of the equation, the factors E and E^2 disappear respectively in the second and third terms in Eq. 1 because of the nondimensionalization that implies an assumption of nonzero field strength.

The three coefficients α, β, and γ are always dimensionless, even when the electrostatic force equation is written in a dimensional form.[9,12,18,19] They are functions of the particle dielectric constant, the spacing between the electrodes, charge distribution on the particle, etc.

To compute the electrostatic force on a charged particle according to Eq. 1, the three coefficients α, β, and γ must be evaluated. To determine the values of α, β, and γ, we use the Galerkin finite-element method for solving boundary-value problems as described by Feng and Hays.[18] This method is especially effective for complicated problem configurations involving several material interfaces. The surface charge distribution on the particle must be specified *a priori* in computing boundary-value solutions to determine the values of α, β, and γ.

Formation of a Dumb-Bell Type Charge Distribution on a Triboelectrically Charged Particle

With limited knowledge of surface charge distributions on toner particles, a dumb-bell type charge distribution appears to be consistent with some measurements.[11,12,16] Here, we speculate on the physical mechanisms that might lead to the formation of dumb-bell type charge distribution on toner particles (as shown in Fig. 3).

From a physical point of view, triboelectric charging (sometimes also called contact charging) occurs when two dissimilar material surfaces are brought into intimate contact. In a two-component charging process, the toner particles are typically mixed with much larger carrier bead particles with different surface material properties. During the charging process, the granular mixture of toner and carrier beads undergoes vigorous small-scale relative motion so that all the toner particles have an opportunity to contact carrier beads to acquire charge. When an electrically neutral toner particle touches a carrier bead, only a small area on its surface where the intimate contact occurs acquires charge. With a small area charged, the toner particle in random motion within the two-component mixture would statistically tend to have the initially charged area in contact with the carrier bead, because of the mechanism of minimizing electrostatic energy. Therefore, a toner particle on a carrier bead surface is very likely to have a charged site in contact with the carrier bead, as speculated by Hays.[12]

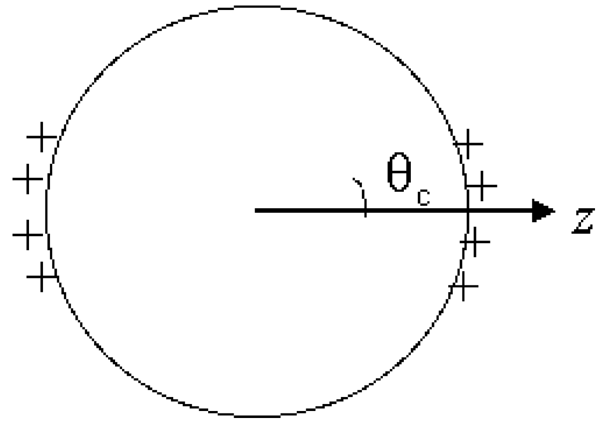

Figure 3. Schematic of a dumb-bell charge distribution on a spherical particle.

Significant charge transfer, however, occurs in the triboelectric charging process only when a toner particle is squeezed by two carrier beads such that intimate contact with the carrier beads happens at the two poles of the toner particle (assuming the toner coverage on the beads is less than a monolayer). In the random motion, when another carrier bead comes near a toner particle that is already attached to a carrier bead at a charged site, it can only contact the area on the toner particle opposite to that charged site, because of the geometric constraints. Because of the tendency of charged sites on the toner to contact carrier beads again and again to acquire more charge, the most likely statistical outcome is that the most significant charge patches reside on opposite poles of the triboelectrically charged toner particles to form the dumb-bell type of charge distribution.

Of course, the experience of each particle in the mixing motions among toner particles and carrier beads may not be the same and charge patch distribution can differ from one particle to another. The dumb-bell charge distribution on particles should be viewed as a statistically reasonable approximation rather than an exact description of a particular toner particle. With this approximation, we find that the theoretical values of electrostatic adhesion force and required electric field strength for detaching toner particles are comparable to the experimental results.

Computational Results

For simplicity, we consider an axisymmetric problem, in which the charge is distributed in cap regions around two opposing poles on the spherical particle surface (see Fig. 3). Thus, the actual distribution of surface charge density on the particle for a given value of the global surface charge density σ (defined by Eq. 2) is described by

$$\sigma/(1 - \cos\theta_c) \quad (3)$$

for $0 < \theta < \theta_c$ and $\theta_c < \theta < \pi$ and zero elsewhere. Here θ_c denotes the polar cap half angle with the polar angle measured from the z-axis. The particle dielectric constant κ_p is assumed to be 3 throughout this work.

For the case of a particle (with $\kappa_p = 3$) resting on a conductive plate with large electrode spacing ($L_+ = 10$ as measured in units of the particle radius R), the computational results yield $\alpha = 1.592$ for a uniform charge distribution (as if with $\theta_c = 90°$) and $\alpha = 52.704$ for a dumb-bell type charge distribution with $\theta_c = 10°$. Thus,

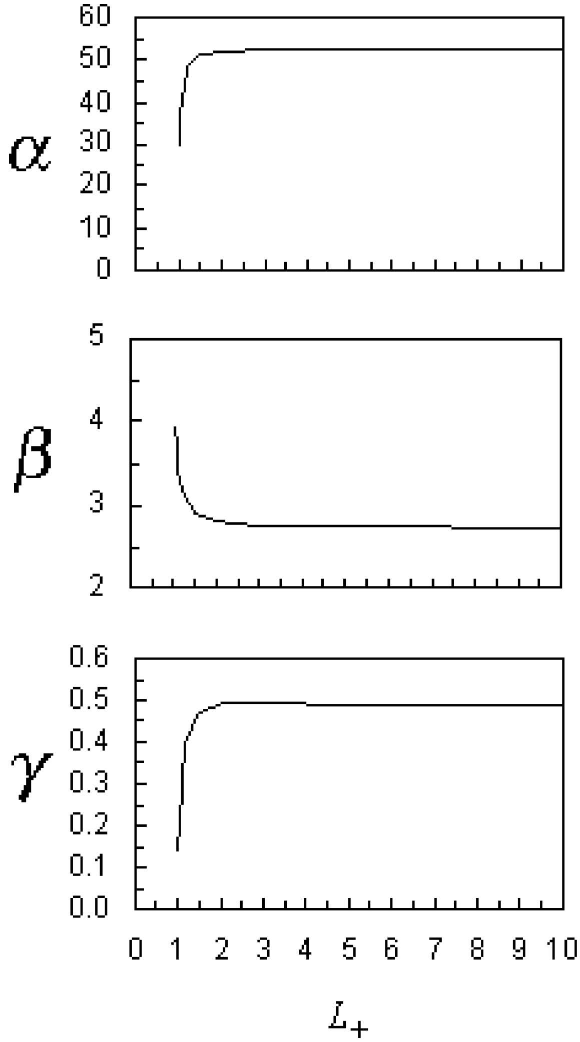

Figure 4. Variations of α, β, and γ versus L_+ for a spherical toner particle with dumb-bell type charge distribution corresponding to $\kappa_p = 3$ and $\theta_c = 10°$.

we assume $\theta_c = 10°$ in the present computations as a reasonable representation for triboelectrically charged toner particles, when comparing the magnitude of corresponding electrostatic adhesion force with the measured values.[7,8,11–17]

Figure 4 shows the computationally determined values of α, β, and γ as functions of the electrode spacing as described by the dimensionless length L_+. For a spherical toner particle with nonuniform charge distribution α decreases whereas β increases upon reducing L_+ and γ varies nonmonotonically with L_+ for the reasons discussed previously by Feng and Hays for a uniformly charged dielectric sphere.[18] Noticeable variations in α, β, and γ for a toner particle with a dumb-bell charge distribution ($\theta_c = 10°$), only occur when $L_+ < 2$, i.e., when the counter electrode is less than one particle diameter away from the center of the particle. Thus, the behavior of electric field detachment of a triboelectrically charged toner particle is expected to be insensitive to the spacing of the electrodes in a parallel-plate capacitor, unless the spacing becomes so small that the counter electrode is nearly touching the particle. In reality, toner has a distributed size. Even in the situation where toner particles provide a self-spacing between donor and receiver surfaces, only a few large particles may be considered as in the small-gap configuration for electric field detachment. Therefore, the model calculations for the situation where a particle rests on a surface in an open space or with relatively large spacing between electrodes should be quite relevant to many situations in electrophotography in describing electric field detachment of charged toner particles.

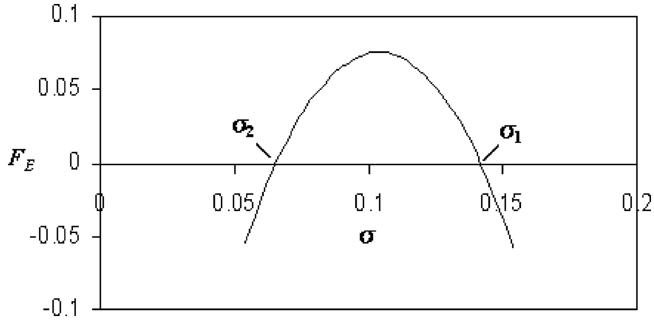

Figure 5. Dimensionless electrostatic force as a function of dimensionless surface charge density on a particle.

Electric Field Detachment of Toner Particles

As indicated in Eq. 1, two roots of σ (denoted here by σ_1 and σ_2) exist when F_E is set to zero. These roots correspond to two threshold values for obtaining an electrostatic detaching force. As discussed by Feng and Hays,[18] σ_1 and σ_2 describe two critical states; one corresponds to an electrostatic force balance when the net charge (first term on right side of Eq. 1) becomes the dominant source of adhesion while the other is the situation when the field-induced polarization (third term on right side of Eq. 1 becomes dominant. As shown in Fig. 5, the net electrostatic force F_E is positive in the interval of $\sigma_2 < \sigma < \sigma_1$ and negative when σ is outside this interval. Thus, for electric field detachment to occur, the necessary condition $\sigma_2 < \sigma < \sigma_1$ must be satisfied.

For a particle of $\kappa_p = 3$ with a dumb-bell type charge distribution in the case of $L_+ = 10$, the computed values for σ_1 and σ_2 are 0.1416 and 0.0658, respectively. If the charge on the particle surface is uniformly distributed (i.e., $\theta_c = 90°$), we obtain 3.3915 and 0.0908 for σ_1 and σ_2, respectively. Clearly, a uniformly charged particle tends to have much greater latitude for electric field detachment than one with a nonuniform charge distribution, as also generally shown by Feng, Eklund and Hays.[19] In typical electrophotographic applications, we have $R = 5 \times 10^{-6}$ (m) and $|Q| = 10^{-14}$ C. According to Eq. 2 with $\sigma_1 = 0.1416$, $|E| > 2.54 \times 10^7$ (V/m) is necessary to detach a triboelectrically charged toner particle from a conductive surface. If the particle charge is uniformly distributed, a field strength of only $|E| > 1.06 \times 10^6$ (V/m) (for $\sigma_1 = 3.3915$) might be sufficient to detach the particle. In reality, the spatial distribution of charge on the toner surface can vary significantly. A layer of toner can have particles of a variety of charge pattern orientations with respect to the substrate. The cases considered here for a uniformly charged particle and a nonuniformly charged particle with a dumb-bell type charge distribution provide important insights into the range of electrostatic force components.

The electric field strength for detaching a charged particle is also theoretically limited by electrostatic adhesion due to a field-induced dipole as represented by the third term on right side of Eq. 1. As a reference, we evaluate the maximum field strength for a charged particle of $R = 5 \times 10^{-6}$ (m) and $|Q| = 10^{-14}$ C. Now from Eq. 2 with $\sigma_2 = 0.0658$ and 0.0908, we obtain another set of necessary conditions that $|E| < 5.47 \times 10^7$ (V/m) and $|E| < 3.96 \times 10^7$ (V/m) for detaching a nonuniformly and uniformly charged particle, respectively.

By taking the derivative of Eq. 1 with respect to σ and setting it to zero, one finds that the maximum electrostatic force for detaching a charge particle is at $\sigma = 2\ \beta/\alpha = (\sigma_1 + \sigma_2)/2$ [because according to Feng and Hays,[18] $\alpha = \gamma/(\sigma_1\ \sigma_2)$ and $\beta = \gamma(\sigma_1 + \sigma_2)/(4\ \sigma_1\ \sigma_2)$* where $\gamma = 0.491$ for $\kappa_p = 3$]. This is in the middle of the interval between σ_1 and σ_2 where the extreme of the parabola in Fig. 5 is located. If the optimal amount of particle charge is evaluated for maximizing the electrostatic detaching force at an electric field strength 3×10^6 (V/m), it is found to be $|Q| = 8.64 \times 10^{-16}$ C and $|Q| = 1.45 \times 10^{-14}$ C respectively for a nonuniformly and uniformly charged particle of $R = 5 \times 10^{-6}$ (m). In view of typical values of toner charge in electrophotography (e.g., $|Q| = 10^{-14}$ C), triboelectrically charged particles with relatively lower charge are expected to be detached more easily according to the theoretical calculations, seemingly against intuition based on common experience in electrophotography.

In reality, however, non-electrostatic force can also play a role in electric field detachment of toner particles. To enable the actual detachment of particles, we should at least have the maximized electrostatic detaching force greater than the non-electrostatic components of adhesion such as van der Waals forces. Assuming that $\sigma = 2\ \beta/\alpha = (\sigma_1 + \sigma_2)/2$ is satisfied, the maximum electrostatic force given by Eq. 1, written in a dimensional form, should become

$$(F_E)_{max} = (4\ \beta^2/\alpha - \gamma)\ \pi\ \varepsilon_0\ R^2\ E^2 = (\sigma_1 - \sigma_2)^2\ \gamma\ \pi\ \varepsilon_0\ R^2\ E^2/(4\ \sigma_1 \sigma_2). \tag{4}$$

Thus, the magnitude of the maximum electrostatic force relates quadratically to the applied field strength. If we consider that $(F_E)_{max} > F_{NE}$ for actual particle detachment, where F_{NE} denotes non-electrostatic components of adhesion, the required electric field strength can be determined by

$$|E|_{min} = 2\ [F_{NE}\ \sigma_1 \sigma_2 / (\pi\ \varepsilon_0\ \gamma)]^{1/2} / [(\sigma_1 - \sigma_2)\ R]. \tag{5}$$

The corresponding amount of particle charge should then be (see Eq. 2 with $\sigma = (\sigma_1 + \sigma_2)/2$ and relationship between α, β and σ_1, σ_2, γ)

$$|Q|_{min} = 4\ R\ (\pi\ \varepsilon_0\ F_{NE}\ \sigma_1 \sigma_2 / \gamma)^{1/2}\ (\sigma_1 + \sigma_2) / (\sigma_1 - \sigma_2). \tag{6}$$

Equations 5 and 6 establish a theoretical basis for understanding the fact that both the particle charge and applied field strength must exceed certain minimum values in order to overcome the non-electrostatic adhesion to enable electric field detachment of charged particles. For effective electric field detachment, the optimal relationship between particle charge and applied field strength should be

$$Q = 8\pi\ \varepsilon_0\ R^2\ E\ \beta/\alpha = 2\ \pi\ \varepsilon_0\ R^2\ E\ (\sigma_1 + \sigma_2) \tag{7}$$

to maximize the electrostatic detaching force.

The values of σ_1 and σ_2 depend on the detailed charge distribution on particle surface, whereas γ is independent of particle charge but a function of dielectric constant of the particle. (If the permittivity of the particle material is the same as the surrounding medium, we should have $\gamma = 0$.) For example, assuming that F_{NE} is about 10 nN (according to Mizes *et al.*),[20] a nonuniformly charged toner particle of $R = 5 \times 10^{-6}$ (m) (with $\sigma_1 = 0.1416$, $\sigma_2 = 0.0658$, and $\gamma = 0.491$), $|E|_{min}$ and $|Q|_{min}$ from Eqs. 5 and 6 would be 1.38×10^7 (V/m) and 3.96×10^{-15} C, respectively. In contrast, if the particle is uniformly charged (with $\sigma_1 = 3.3915$, $\sigma_2 = 0.0908$, and $\gamma = 0.491$), $|E|_{min}$ and $|Q|_{min}$ from Eqs. 5 and 6 would be 1.82×10^6 (V/m) and 8.78×10^{-15} C, respectively. The fact that both $|E|_{min}$ and $|Q|_{min}$ are proportional to the square root of F_{NE} indicates that their magnitudes are expected to vary by a factor of about 3 for an order of magnitude change in F_{NE}. For triboelectrically (or nonuniformly) charged particles, the applied electric field strength required for detachment [$|E|_{min} = 1.38 \times 10^7$ (V/m)] is much higher than the air breakdown limit for an open space [about 3×10^6 (V/m)]. Fortunately in electrophotography, the electric field detachment of toner particles usually occurs in narrow gaps where the air breakdown limit is raised significantly as described by the the Paschen curve.[3]

If the components of electrostatic force are evaluated with $|Q|_{min}$ and $|E|_{min}$ given by Eqs. 5 and 6, respectively for a nonuniformly and uniformly charged toner particle, we have the dimensional electrostatic adhesion due to the attraction between the particle charge and its image (corresponding to the first term on the right side of Eq. 1), i.e.,

$$\alpha\ Q^2 / (16\ \pi\ \varepsilon_0 R^2) = \gamma\ Q^2 / (16\ \pi\ \varepsilon_0\ R^2\ \sigma_1 \sigma_2), \tag{8}$$

equal to 74.2 nN and 11.0 nN. Likewise, respectively for a nonuniformly and uniformly charged toner particle, the dimensional Coulomb force (corresponding to the second term on the right side of Eq. 1), i.e.,

$$b\ \ Q\,E = g\ \ Q\,E\ \ (s_1 + s_2) / (4\ s_1 s_2), \tag{9}$$

equals 149 nN and 22.1 nN, and the dimensional electrostatic adhesion due to the attraction between the field induced dipole in the dielectric particle and its image (corresponding to the third term on the right side of Eq. 1), i.e.,

$$\gamma\ \ \pi\ \varepsilon_0\ R^2\ E^2, \tag{10}$$

equals 64.9 nN and 1.13 nN. Indeed, for typical triboelectrically charged toner particles, (unlike the uniformly charged particles), the magnitudes of electrostatic force components are much greater than that of non-electrostatic adhesion (of about 10 nN), as discussed previously by Hays.[21] Thus, electric field detachment of triboelectrically charged toner particles becomes primarily a consequence of balancing among large electrostatic force components given by Eq. 1 or Eqs. 8 through 10. The non-electrostatic component of adhesion is relatively small and may be neglected unless the required electric field strength for actual particle detachment is to be evaluated by Eq. 5. Therefore, the typical behavior of triboelectrically charged toner particles in terms of electric field detachment for electrophotography ap-

* Note a typographical error in Ref. 18 where the factor 4 is missing in the denominator of the formula for *b*.

plications should be reasonably well described by considering electrostatic force components given by Eq. 1 or Eqs. 8 through 10.

Noteworthy here then is the importance of the global surface charge density on a particle $Q/(4\pi R^2)$, in evaluating electrostatic force described by Eq. 1 (rather than Q/M or $3Q/(4\pi\rho R^3)$ as a parameter commonly referred to in electrophotography). The theoretical implication of Eq. 1 is that if all the toner particles are charged according to $Q \sim 4\pi R^2$ and have the same orientation on a surface with respect to their charge patches, the field strength for toner detachment should be the same regardless of particle size. Typical triboelectrically charged toner particles, however, are found to actually follow a relationship somewhere between $Q \sim R$ and $Q \sim R^2$, although $Q \sim R^2$ is commonly assumed in most model calculations.[22] Thus, among toner particles of distributed sizes, larger particles may be more easily detached by an electric field than smaller particles. Yet the general behavior of toner particles in electric field detachment is expected to be independent of the mean particle size, since a comparison of different toners indeed show a $Q \sim R^2$ relationship in terms of mean values.[23]

Conclusions

Theoretically, the electrostatic force on a charged toner particle in an applied electric field can be represented by three terms corresponding to different sources. The electrostatic adhesion force can arise from either the net charge on the particle or polarization of the particle in an applied electric field. To obtain an electrostatic driving force as represented by the Coulomb force, however, the particle must have a net charge in the presence of an external electric field. If the applied electric field is assumed to be nonzero as is the case for electric field detachment, a concise dimensionless form of the electrostatic force equation can be formulated. The dimensionless equation so formulated renders a simple quadratic relationship between the dimensionless electrostatic force on an isolated toner particle and dimensionless surface charge density on the particle defined as the global surface charge density scaled by the applied electric field strength. The two roots of the quadratic equation represent the two threshold states for obtaining electrostatic detaching force on the charged particle. The mean value of the two roots gives the maximum electrostatic force for particle detachment.

Although a uniform charge distribution on a spherical particle is ideal for theoretical analysis, it does not lead to theoretical results that agree with experimental observations of electric field detachment of triboelectrically charged toner particles. Based on previous experiments and associated analyses, we consider a dumb-bell type surface charge distribution on a spherical particle to approximate triboelectrically charged toner particles with a nonuniform surface charge distribution. With this approximation, the theoretical values of electrostatic adhesion force and required electric field strength for detaching toner particles become comparable to the experimental measurements. In reality, the spacial distribution of charge on toner surface can vary significantly. A layer of toner can have particles of a variety of charge pattern orientations with respect to the substrate. In the present work, two extreme cases are considered for a uniformly charged particle and a nonuniformly charged particle with a dumb-bell type charge distribution to provide quantitative insights into the range of electrostatic force components.

The computational results for a particle with a dumbbell charge distribution show that the behavior of electric field detachment is insensitive to the electrode spacing, unless the spacing becomes so small that the counter electrode is nearly touching the particle. Because the size of toner particles is distributed, even in the situation where toner particles provide a self-spacing between donor and receiver surfaces, only a few large particles may be considered as in the small-gap configuration for electric field detachment. Thus, the model calculations for the situation where a particle rests on a surface in an open space or with large electrode spacing should be quite relevant to many practical cases in electrophotography when considering electric field detachment of charged toner particles.

Realistically, electric field detachment of charged particles cannot occur near the thresholds for electrostatic detaching force, because of the ubiquitous van der Waals adhesive forces and adhesion from other sources. A minimum electric field strength and the corresponding minimum particle charge are required to provide the maximized electrostatic detaching force overcoming those non-electrostatic adhesion forces. The theoretically evaluated magnitudes of the force components indicate that electrostatic force components are indeed much greater than the non-electrostatic force components for triboelectrically charged toner particles. Therefore, considering the electrostatic force components should often be adequate in describing the behavior of charged toner particles in electric field detachment.

Because the nondimensional electrostatic force can be theoretically described by a single variable defined as the ratio of the global surface charge density on the particle and the applied electric field strength, the global surface charge density of toner particles becomes an important parameter. Noteworthy is that if the particle charge is proportional to the particle surface area, the electrophotographic performance of a triboelectrically charged toner is expected to be independent of particle size.

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