Particle Size-Selective Transfer

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Abstract

For every jumping powder development the competition between adhesion forces and the local electrical pull-off force determines whether development (transfer) is possible or not. With the general assumption that the toner charge is proportional to r^n, $n \leq 2$ for small particles, while for some developer systems it tends to become proportional to r for larger sizes, a theoretical model for this phenomenon was developed.

Our calculations predict the influence of magnetic adhesion, toner charge, nonuniform toner surface-charge density, choice of materials, and electrical field strength on a particle size-selective development. A strong indication of the relation between nonuniform toner surface-charge density and particle size-selective transfer is presented. Also an explanation of particle size-segregated toner layers is suggested.

Ideas on how to decrease the selectivity are suggested on the basis of our investigation.

Introduction

Particle size-selective transfer as a reason for unstable print/copy process is known ever since monocomponent development was applied to xerographic systems. Canon, in their SX engine, overcame instabilities and also improved resolution by superimposing alternating electrical fields in jumping development.

Many theories treat different parts of the selectivity mechanism and possible solutions to improve stability. While working with monocomponent development systems and also a TonerJet process that uses such a development subsystem, we felt the need for a simple (i.e. usable) theory telling us the influence of the different parameters as a practical guideline for engineers. In this sense a good balance between simplicity and complexity has to be found. Because the transfer of toner from the developer to the photoconductor and from the photoconductor to the paper uses electrostatics, a theory involving electrostatic forces should be applicable to these steps in xerographic printing.

General Considerations

Electrically charged particles stick to a surface because of electrical interactions (monopole and multipole), magnetic adhesion, and interparticle forces. Particles are developed/transferred if the force from the locally applied electrical field is larger than the sum of these adhesion forces. If now a certain amount of particles exhibits an excessive adhesion force these particles will statistically occupy the places of particles previously developed and, depending on the amount of printing, the process will stop after a while. In a triboelectric charging system, undeveloped particles will be moved or replaced (circulated) due to the mechanical force in the charging zone, i.e. the development will not really stop but will have a poorer and poorer transfer in the transfer zone. So the first necessary, but insufficient, precondition for stability is that the surface of the sleeve must not be saturated with such particles. The electrical charge of the toner particles, the content of magnetite, and the geometrical shape are distributed quantities. From this it is evident that their adhesion force also is distributed. The degree of selectivity is mainly determined by the width of this distribution.

Transfer Function

A first overview of selectivity is gained if the transfer probability vs. toner size is recorded. This transfer function should not be mistaken for the transfer rate commonly used in xerographic techniques. Two mechanisms contribute to a particle size-selective transfer. First, if more than one monolayer is formed on the developer surface, generally an enrichment of larger particles is found on it. An example of this can be found in Figure 1. This selection is self-aligning, i.e. the same kind of enrichment will be active until all particles are transferred. This means that this mechanism is not the primary reason for an unstable print process, since it has no place in the particle size distribution where charging and transferring toner particles to the developer sleeve will stop.

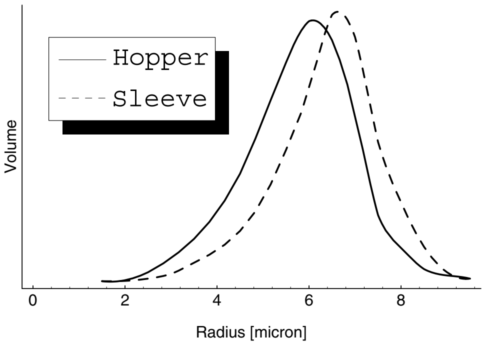

Figure 1. Particle size distribution in toner hopper and on developer surface.

Particle size-selective transfer will occur from the developer surface when the local electrical field is too weak to overcome the particle-specific adhesion forces. This paper mainly deals with this effect.

In order to achieve a first experimental overview, one can measure the transfer rates by means of several narrowly size-distributed toners with different average particle sizes. Such transfer curves contain all information needed to match the size distribution of the toner to the print process. If only one broad distributed toner is used for a quick (and uncomplete) overview, one has to take into account that this transfer behavior is biased by the enrichment of the larger particles on the developer surface. The reliability of this method stands and falls with the number of monolayers on the developer. The method suggested above gives reliable results if the particle size distribution in the reservoir is approximately the same as on the developer surface, e.g. when the limit of a monolayer formation is valid or a narrowly size-distributed toner is used.

Figure 2 shows the transfer function for a fictional system as an illustration. Toners successfully used in such a system must exhibit particles in the range where the transfer function is near 1 and reasonably flat, to ensure long time-stability. Particles in the region where the transfer function has fallen to zero have to be avoided. These two demands can be met by the use of a narrowly size-distributed toner with its average size located at the appropriate position. However, this is not the only possible choice.

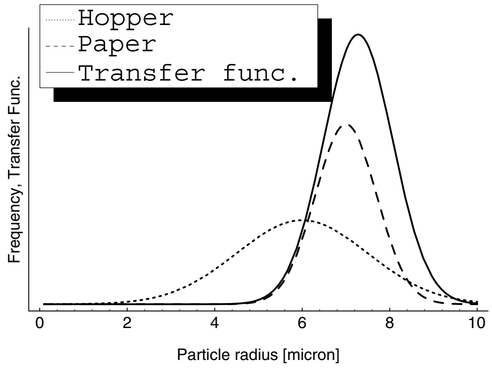

Figure 2. Transfer function and particle size-distribution in the hopper and on the paper (fictional system).

Toner Particle Charge

Several papers discuss the relationship between toner radius r and its charge q. Since the charge on a toner particle is located mainly on the surface it is expected that $q \sim r^n$, $n = 2$. Terris and Jaffe[1] found $n = 1.4$ to 1.6 for a small r, and $n = 1$ for a large r. The Ricoh group[2] found that $n \approx 2$ for $r < r_0 = 6$ µm and that q is independent of r for $r > r_0$. We found that $n \approx 1.4$ throughout the r range when charging a toner sample in a charge spectrometer.

The conclusion from these observations is that n seems to depend on the shape of toner particle and charging technique and r_0 may or may not exist depending on charging technique. This can mathematically be expressed in the following form:

$$q(r) = \begin{cases} q_0 \cdot r^n & r \le r_0 \\ q_t \cdot r & r > r_0 \end{cases} \tag{1}$$

When toners are charged they get a nonuniform charge distribution on the toner particle surface. Hays[3] described such behavior and uses α as a correction to the image force to describe the influence of the nonuniformity. The range of α is theoretically 1 to infinity, if we do not take into account sparking and tunneling when the effective charge becomes a point charge in the vicinity of the developer sleeve surface. Adding the correction factor for a dielectric surface we end up with equation 2. Further, M. Lee and J. Ayala[5] showed that regions with high charge density are likely to be close to the developer sleeve surface.

Hays[3] also calculated the electrostatic force on a dielectric sphere resting on a conducting substrate and states that, due to the polarization of the dielectric sphere, an additional electrostatic force is introduced. This force is also depending on the dielectric constant of the toner. Adding the correction factor for a dielectric surface we end up with equation 7.

Forces on Toner Particles in a Monolayer

Forces active on a charged particle attached to a surface are

$$F_i = \alpha \frac{k_s - 1}{k_s + 1} \frac{1}{4\pi\varepsilon_0} \frac{q^2}{4r^2} \tag{2}$$

$$\mathrm{F_v} = func(r) \tag{3}$$

$$F_m = \frac{\mu_p - 1}{\mu_p + 2} r^3 H \cdot \nabla H \tag{4}$$

$$F_g = m \bullet g \tag{5}$$

$$F_f = \frac{m \cdot v_s^2}{r_s} \tag{6}$$

$$F_c = \beta q \mathbf{E} + \gamma \pi \varepsilon_p \frac{k_s - 1}{k_s + 1} (2r \cdot \mathbf{E})^2 \tag{7}$$

where F_i = image force, k_s = relative permittivity of the surface, F_v = Van der Waal forces, F_m = magnetic adhesion for magnetic toner, F_g = gravity, F_f = centrifugal force, F_c = Coulomb force due to the local electrical field used for development/transfer corrected with the induced polarization force, q = toner charge, ε_0 = permittivity of free space, r = particle radius, m = particle mass, $\mathbf{E}$ = local electrical field strength, μ_p = permeability of the toner, β, γ = correction factors due to the polarization of the toner particle dielectric body, ε_p = permittivity of the toner particle, $\mathbf{H}$ = magnetic field strength, v_s = surface speed of the developer sleeve/OPC-drum, r_s = radius of the same, and $g = 9.81$ m·s^{-2}.

A first estimate shows that gravity contributes less than 1% of all forces. Equation (5) therefore is omitted in the following. The centrifugal force (6), at normal speed in printers, is of about the same magnitude as the gravitational force and therefore is omitted for the same reason.

Because the distance from the magnetic core to the sleeve is large (>500 µm) compared to the particle size, i.e.

the magnetic field strength is independent of the particle size, we simplify equation (4) to

$$F_m = C_m \bullet r^3 \tag{4a}$$

where F_m is the magnetic adhesion which is proportional to the content of magnetite and thus proportional to the particle volume.

The Van der Waals force (VdW) is subject to controversy in the literature. There are some indications that the VdW force is significant[4] and other indications that it is not.[5] We do not know if this force is significant but we found that it is not needed in order to describe the particle size-selective transfer. Further, the VdW force is an adhesion force and will not change the findings except than it might increase the selectivity. The VdW force therefore is considered to be unimportant for this theory and is excluded from further consideration in this paper, except for a minor remark in the section about thick toner layers.

Using equation (1) in (2) and (7) we get

$$F_i = \frac{k_s - 1}{k_s + 1}\frac{\alpha}{4\pi\varepsilon_0}\cdot\begin{cases} q_0^2\dfrac{r^{2(n-1)}}{4} & r \le r_0 \\ \dfrac{q_t^2}{4} & r > r_0 \end{cases} \tag{2a}$$

$$F_c = c_a(2r\cdot\mathbf{E})^2 + \beta\mathbf{E}q_0 r^n \tag{7a}$$

for $r \le r_0$ and

$$F_c = c_a(2r\cdot\mathbf{E})^2 + \beta\mathbf{E}q_0 r$$

for $r > r_0$ with

$$c_a = \gamma\pi\varepsilon_p\frac{k_s - 1}{k_s + 1}$$

Now, the condition for a toner particle to be developed/ transferred is

$$F_c \ge F_i + F_m \tag{8}$$

described by equations (7a), (2a), and (4a).

If we divide (8) with the particle mass we end up with the acceleration of the particles. Using the acceleration instead of the net force makes it easier to see the influence of the different parameters. After a particle has left the surface all electrical adhesion forces will fall to approximately zero within a short distance from the sleeve and the particle will move under the influence of the electrical and magnetic fields only. In the subsequent set of equations, A denotes the acceleration.

$$A_i = \alpha\frac{k_s - 1}{k_s + 1}\begin{cases} c_{i,1}q_0^2 r^{2n-5} & r \le r_0 \\ c_{i,2}q_t^2 r^{-3} & r > r_0 \end{cases} \tag{2b}$$

$$A_m = C_m = \text{constant} \tag{4b}$$

$$A_c = c_c\,(c_a r^{-1}\mathbf{E}^2 + \beta\mathbf{E}q_0 r^{n-3}) \tag{7b}$$

for $r \le r_0$ and

$$A_c = c_c\,(c_a r^{-1}\mathbf{E}^2 + \beta\mathbf{E}q_t r^{-2})$$

for $r > r_0$.

The threshold for development then is

$$A_c = A_i + A_m \tag{9}$$

Looking at a nonmagnetic toner ($A_m = 0$) we will find an equilibrium where $A_i = A_c$ when

$$E = q_0\cdot r^{n-2}\left(-c_e \pm \sqrt{\frac{\alpha c_i}{\gamma\pi\varepsilon_p c_c} + c_e^{\,2}}\right) \tag{10}$$

with

$$c_e = \frac{\beta(k_s + 1)}{2\gamma\pi\varepsilon_p(k_s - 1)}$$

for $r \le r_0$.

If we let the charge of the toner particle be proportional to r squared, equation (10) will turn into a constant which is tantamount to the equilibrium being independent of the toner particle radius. This further means that the lower the n, the more the optimal electrical field strength depends on the particle size. In the case of $n = 2$, either all or no particles will be developed depending on *q/m* at a given electrical field strength.

In the equations presented we have a number of parameters that affect the development. To develop a systematic understanding of how these parameters influence the development we plot the accelerations of a toner particle as a function of the toner particle radius. In subsequent figures, different parameters are varied, one at a time, in order to show their influence. First is a group showing the influence of **E**, α, *n*, and *q/m* when no magnetic force is taken into account. The particle radius threshold used[2] is $r_0 = 6$ μm. For all curves drawn with a solid line the same set-up of parameters is used. This set-up is: $\mathbf{E} = 1.5$V/μm, $\alpha = 1$, $n = 2$, $q/m = 10$μC/mg $k_s = \infty$ (electrically conductive surface), and $\rho_{mtrl} = 1000$ kg/m^3.

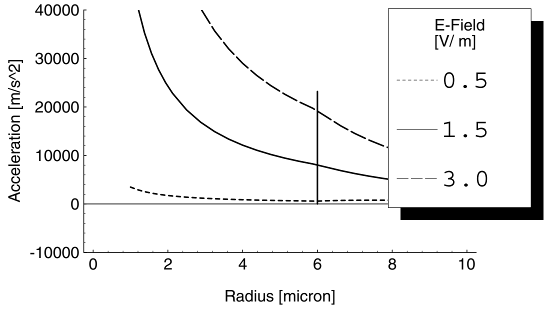

Figure 3. Dependence on E ($A_m = 0$).

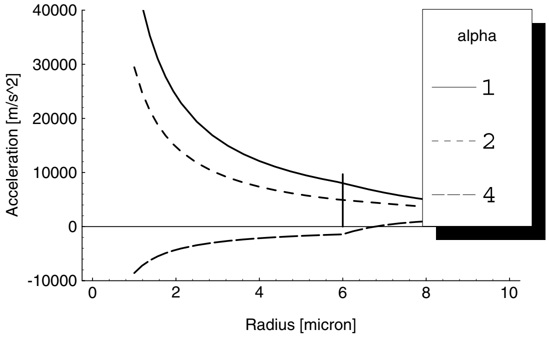

Figure 4. Dependence on α ($A_m = 0$).

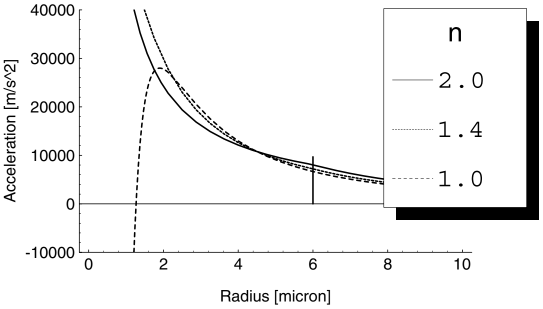

Figure 5. Dependence on n (A_m = 0).

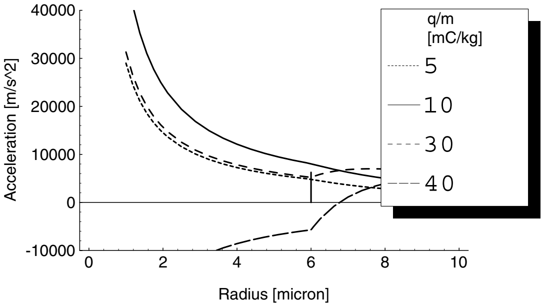

Figure 6. Dependence on q/m (A_m = 0).

In Figure 6 we can see that we will have a particle size-selective transfer if the charge of the particle is too high. We can also see, in Figure 5, that a low exponent n will influence the particle size-selectivity for small particles. The same happens if the charge distribution on the toner particle is nonuniform (see Figure 4). In the section on toner particle charge we saw that the charge is not always depending on r^2 but more likely on r^1.[4] This, together with the knowledge that the charge distribution on the toner particle surface is not uniform, gives us the following figures:

This shows us that we will have a particle size-selective transfer if the charge distribution on the toner particle surface is not uniform and that the particle charge is unrelated to r squared. The lower the n and the more inhomogeneous the charge distribution on the particle surface, the more particle size selection will occur. In fact, the distribution of transferred particles will be cut off at both sides, giving a bandwidth filter. We get the same effect when adding the magnetic adhesion force. In equation (4b) we see that the acceleration due to the magnetic force is constant for all particle sizes and will simply have the effect of shifting the acceleration curves downwards.

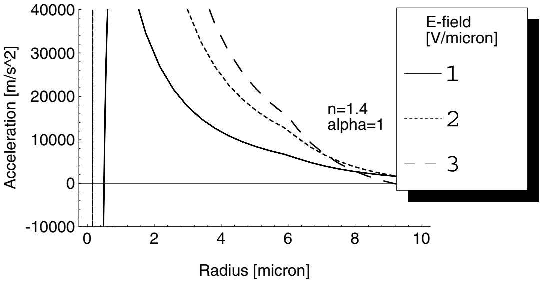

Figure 7. Acceleration with n = 1.4 and α = 1.

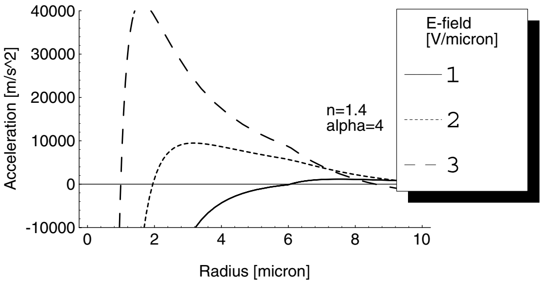

Figure 8. Acceleration with n = 1.4 and α = 4.

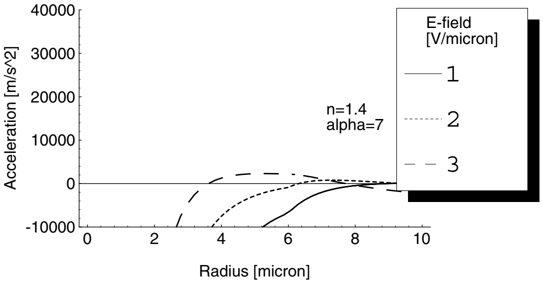

Figure 9. Acceleration with n = 1.4 and α = 7.

Changing the surface on the developer sleeve or on the photoconductor is relatively easy. The influence on the acceleration, shown in Figures 10 and 11, indicates that the influence on the transfer is significant when $n < 2$ and $\alpha > 1$. The materials listed in the legend are just examples of materials with the indicated k_s.

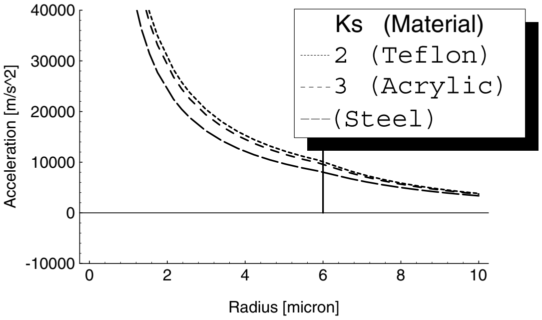

Figure 10. Influence on the acceleration for different materials, n = 2, α = 1.

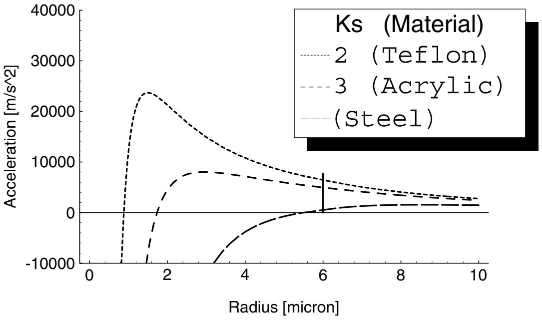

Figure 11. Influence on the acceleration for different materials, n = 1.4, α = 4.

Thick Toner Layer

In most cases more than a monolayer sticks to the developer surface. The total layer is determined by the competition between the net adhesion forces and the detachment forces applied during the doctoring process (no matter whether noncontact or contact-doctoring is applied). A large contribution to the adhesion results from electrical forces. Thus, the layer thickness actually formed is strongly affected by the stability of the toner charge. Obviously (see Figure 1), larger particles are overrepresented in the toner layer on the developer. To give an explanation of this phenomenon we examine the formation of the next monolayer on an already existing toner layer. A particle can stick if the sum of the image force, magnetic adhesion, and a minor contribution of the VdW force is larger than the electrical repulsion:

$$F_{rep} < F_i + F_m + F_v \tag{11}$$

with

$$F_{rep} = \frac{q \cdot q_s}{16\pi\varepsilon_0 r^2} \tag{12}$$

where q_s = surface charge due to toner already sticking.

We first omit the magnetic adhesion, and then consider the quotient F_{rep}/F_i, and use (1), (2) and (12)

$$\frac{F_{rep}}{F_i} = \frac{1}{\alpha}\frac{k_s + 1}{k_s - 1}\frac{q_s}{q_0} r^{-n} \tag{13}$$

with $n \leq 2$ and $r < r_0$.

From this we see (assuming α is constant) that the quotient between adhesion and repulsion decreases with increasing particle size and therefore larger particles have a greater chance to stick. The effect is even enhanced with magnetic toner because the (additional) magnetic adhesion rises with the cube of the particle size. The degree of this segregation is, among other parameters, influenced by the exponent n. The higher the n, the more segregation is to be expected. As long as the particles transported into the development zone can be pulled off at a comparable rate by the electrical field this segregation will not influence the stability of the print process. The particle size distribution in the reservoir will change towards smaller particles during printing, as mentioned before. Depending on the actual size distribution the formation will undergo self-alignment. In the case of an unstable process (smaller particles cannot be transferred) this segregation can lead to a stable process during the printing of the first few pages, followed by a rather abrupt decrease of image density. In other words: Segregation can cover instability at the very beginning if, due to the doctoring process, a thick toner layer is allowed to be establish it self. The only chance, however, to end up with stable print conditions is to match the toner size distribution and the transfer behavior of the process to one another, i.e. all sizes in the toner hopper can be transferred in the transfer zone. The conditions for transfer are described in section "Forces on toner particles in a monolayer".

Limitations of the Model

Though the actual selective particle size-depletion is not as sharp as described, due to the fact that all parameters are distributed quantities, the theory tells us that there are mechanisms that make the transfer particle size-selective. Further, no interparticle forces are taken into account and the toner particles are considered spherical. Nothing in the theory assumes or predicts that the charge nonuniformity factor, α, is depending on the particle size but such a relationship will affect the mechanism. The electrical field strength during transfer is assumed to be constant. This is only valid for direct electrostatic printing such as TonerJet. In the case of xerographic printing, however, the electrical charge of already developed/transferred toner partly compensates the local electrical field. This self-saturating effect occurs anyway and is treated in many textbooks. There are indications of chemical affinity between the toner and the OPC surface for some systems. These effects can not be treated on a global scale while, on the other hand, the lack of chemical binding is a necessary precondition for every stable working system.

Discussion

The work above shows the importance of a uniform charge distribution on the particle surface. Optimum conditions are achieved if the toner charge is proportional to its surface. In this case the region where development can occur is at a maximum. If a homogeneous charge distribution over the particle surface is achieved the proper choice of material constants has a minor influence on further optimization. Careful adjustment of the magnetic adhesion is needed. A too high magnetic adhesion will narrow the region of development on both sides—for the large particles and the small ones as well—which means that a particle size filter can be established. A particle size-segregated toner layer formation will take place prior to toner transfer if more than monolayer formation is allowed by the doctoring process. In short, this work shows that in order to have a stable print process with respect to particle size-selective transfer, the pull-off force acting on the toner particles closest to the developer sleeve/photoconductor must surpass the adhesion forces. The best way to accomplish this is to have a uniform charge distribution on the toner particle and the toner particle charge proportional to the toner particle surface (i.e. a ≈ 1 and $n \approx 2$ or, as we like to call it, a good charge quality). The second best way to increase the print process stability, if a and n can not be improved, is to select a material on the developer sleeve/photoconductor with as low a dielectric constant k_s as possible.

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