Theory of Blade Cleaning

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Abstract

Rolling detachment of toner by contact with the cleaning blade is the most important process in removing well-adhered toner from an adhesive substrate. The viability of the process is determined by the balance between the elastic force exerted by the blade on the particle and adhesion and friction forces exerted by contact with the substrate and blade. From analysis of these forces we obtain a vision of the cleaning latitude space. We give a quantitative analysis of the conditions under which the blade cleans toner in terms of parameters such as blade load, blade tip angle, tribo and surface energy. Much of the function of blade cleaners can be understood by the action of these parameters on the shape of the cleaning latitude space.

I. Introduction

Recently there has been renewed interest in understanding the mechanics of blade cleaning of toner from photoreceptor and intermediate belt surfaces. This renewed interest has come about from the arrival of new toner materials, as well as new photoreceptors with decreased adhesion and friction. Finally, new system requirements have necessitated new toner additive packages. For example, biased charging rolls have been introduced, requiring that insulating lubricants such as zinc stearate not be used to enable cleaning since these insulating lubricants cause charging problems. This has led to a new look at an old technology.

On the surface, the blade cleaner appears to be the essence of simplicity. There are no moving parts to break, there are no power supplies. We take an elastomer blade and wipe the substrate surface with it, removing untrans-ferred toner particles, free additives, paper debris, carrier beads that have escaped the developer housing, etc. However, in practice it is found that the blade cleaner is more complex. There are several problems of interest related to blade cleaning:

- blade holder setup;
- blade material hardness limitations to give conform-ability compatible with surface roughness and run-out;
- blade hardness requirements to give sufficient detach-ment force for removal of strongly adhered particles;
- requirements of the toner particle size distribution;
- blade rebound to take into account the tip dynamical requirements;
- blade ability to trap free toner additives;
- the details of the toner additive package, it's system interactions, the stability of the additive package, and the several possible methods of additive function, and it's optimization;
- interactions between blade, toner, and substrate (assumed to be a photoreceptor) geometrical and physical parameters that determine single or multi-particle detachment capability.

It's beyond the time and space requirements of the present paper to discuss what is known in all of these areas. In the present paper we concentrate the last bullet above, the physical interactions between the blade, toner, and substrate which determine whether or not a toner particle will be detached from the substrate surface.

Goel,[1] in an internal Xerox report, outlined the physics of several cleaning subsystems, among them blade cleaning. Much of what we understand about blade cleaning is based on the analysis of force balance equations first developed by Goel.

In the next section we present Goel's equation for rolling detachment obtained from an analysis of the torque moments on a single toner. We then present an analysis of the latitude space for rolling detachment based on study of that equation. While the analysis presented here will not answer all of the questions with respect to blade cleaning, it provides a basis on which these questions can be addressed. We end with a discussion of results found from a more complete analysis of detachment mechanisms in blade cleaning, and their implications for trends in xerography, such as the trend towards smaller toner, higher tribo toner, and spherical toner.

II. Rolling Detachment and its Latitude Space

There are several detachment mechanisms discussed with blade cleaning, among them sliding, lifting, impulsive, and rolling detachment. Analysis of these mechanisms indicates that rolling detachment is probably the dominant mechanism in most areas of latitude space for toner detachment against the cleaning blade. The good-cleaning areas of latitude space for the other mechanisms are found to be smaller than the good cleaning latitude domain for rolling. This mechanism will be explored here. The approach given here can be used to outline the latitude space for these other mechanisms.

A cleaning blade will typically be set up a particular blade holder elevation angle with respect to parallel to the substrate. A typical value might be 15 degrees. In *wiper mode*, friction acts to pull the blade-substrate contact point away from the bulk of the blade. In *doctor mode*, friction acts to push the blade tip back underneath the bulk of the blade. This tucked configuration of the doctor blade is that typically used in blade cleaning. On a microscopic scale such as seen by the toner particle (see Fig. 1) a typical blade tip angle θ between the blade and the toner particle might be on the order of 30°.

For rolling detachment Goel argues that the counter clockwise moment should exceed the clockwise moment in Fig. 1. The resulting condition for particle detachment is:

$$\cos(\theta)[\mu_{TB}-\mu_{TP}] + \sin(\theta)\,[1+\mu_{TB}\mu_{TP}] + \mu_{TB} > \mu_{TP}\, F_a/F, \qquad (1)$$

where μ_{TB} is the toner-blade friction coefficient, μ_{TP} is the toner-photoreceptor (or other substrate) friction coefficient, F_a is the toner photoreceptor adhesion force, and F is the force of the blade on the toner particle. These quantities are illustrated in Fig. 1.

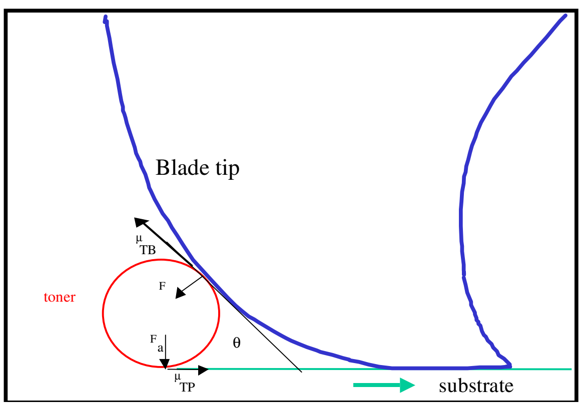

Figure 1. Schematic illustration showing the geometry and parameters describing the toner-blade –substrate contact.

Goel notes that there is a critical contact angle for detachment. If the blade tip contact angle, θ, against the toner exceeds this critical angle, θ_R, detachment and cleaning will occur. If it does not exceed this contact angle, a cleaning failure results. Goel's solution for the critical angle didn't consider toner adhesion. A more complete analysis shows that Eq. (1) can be solved exactly to obtain an expression for the critical cleaning angle, θ_R, in terms of the blade and adhesion forces as well as friction coefficients:

$$\theta_R = 2\tan^{-1}\left[\frac{1 + \mu_{TB}\mu_{TP} - \{[\mu_{TB} - (F_a/F)^2+1]\mu_{TP}^2 + 2(F_a/F)\mu_{TB}\,\mu_{TP} + 1\}^{1/2}}{[(F_a/F)-1]\mu_{TP}}\right]. \qquad (2)$$

Although Eq. (2) presents an exact solution of the Goel equation, the playoff between variables is not obvious: the shape of the latitude space is unclear. These questions are the subject of the remainder of the paper.

Due to fluctuations in toner loading on the substrate, friction variations between blade and substrate, load variations due to runout, variations in local lubricant concentration, stick-slip behavior of the blade, etc., the blade will undergo a combination of both random and periodic oscillations around its' average tip angle. During these tip oscillations it is possible for the tip angle to fall below the critical cleaning angle, resulting in cleaning failures. For good cleaning, we want the critical angle, given by Eq. (2), to be as small as possible: zero or negative is desirable and possible.

It is useful to define a cleaning latitude, L, in degrees, that describes the acceptable oscillation range over which the blade will clean of the blade tip angle around it's average orientation, θ. Thus, the latitude, L, is defined by $L = \theta - \theta_R$ where θ_R is given by Eq. (2). If θ_R is zero, or negative, then the latitude is large and the blade will always clean, regardless of the size of the random oscillations around it's average direction. If, however, the latitude is only a few degrees, poor cleaning can be expected. When $\theta_R \geq \theta$, a cleaning failure will always result. From the solution, Eq. (2), of the detachment equation we can obtain a view of the latitude space for rolling. Substituting Eq. (2) into the definition of latitude, and rearranging, we obtain curves of constant cleaning latitude in μ_{TB}-μ_{TP} space described by:

$$\mu_{TB} = \frac{\{[(F_a/F) - 1]\tan^2[(\theta-L)/2] + (F_a/F) + 1\}\mu_{TP} - 2\tan[(\theta-L)/2]}{2\tan[(\theta-L)/2]\mu_{TP} + 2}. \qquad (3)$$

The region of perfect cleaning is bounded by the surface where θ=L (i.e., the blade cleans all the way from it's set angle down to θ=0). From Eq. (3) we find this boundary is given by:

$$\mu_{TB}^{Clean} = \{[1+(F_a/F)]/2\}\,\mu_{TP}. \qquad (4)$$

Thus, the boundary between perfect and imperfect cleaning is a straight line in μ_{TB}-μ_{TP} space (hereafter we call this latitude space) with a slope of $[1+(F_a/F)]/2$. The good cleaning domain is indicated in Fig. 2. As we see from Eq. (4), as the ratio F_a/F increases, the acceptable cleaning domain decreases. It is interesting that this boundary does not depend on the blade tip angle, except possibly implicitly through the blade force, F. This is in general agreement with experimental observations, which show that if the blade is cleaning well, it isn't sensitive to the blade holder angle. When the blade is failing to clean, minor tinkering with the blade holder angle won't fix it (Nero Lindblad, personal communication). Similarly, Eq.(3) with vanishing latitude, L=0, gives the equation for the cleaning failure boundary. This region is also indicated in Fig. 2. This boundary does depend on toner-blade tip contact angle.

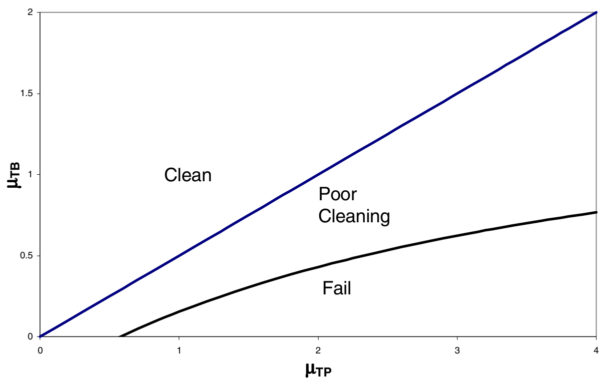

Figure 2. Cleaning latitude plot for rolling detachment for $F_d/F=0$ and $\theta=30°$. As the ratio F_d/F increases the linear lower border of the Clean zone rotates upward, as indicated by Eq. (4). The size of the Fail zone also increases with increasing F_d/F.

The size of the cleaning failure region depends not only on the force ratio F_a/F, but also on the angle of the blade tip. As the magnitude of the ratio F_a/F grows, not only does the good cleaning region size shrink, the size of the intermediate (poor) cleaning region also shrinks. With increasing adhesion the transition from excellent cleaning to cleaning failure becomes more abrupt.

In the present section we have discussed the cleaning latitude in terms of a space μ_{TB}-μ_{TP}. In general, we don't know where toner, blade, and photoreceptor lie within that space. Indeed, we expect toner-substrate friction coefficients to depend on the roughness of the substrate. Measurements show that the submicron substrate roughness varies widely from point to point on the surface. Studies show that the asperity height- asperity separation space location varies approximately logarithmically with the copy count over the course of a photoreceptor life. Similarly, we expect the toner-photoreceptor friction coefficient to vary widely over the surface, and vary throughout the life of the substrate.

We do know however, that we want the cleaning portion of that space to be as large as physically possible. We have seen that the size of the cleaning portion of that space decreases as the quantity F_a/F grows. When the ratio F_a/F approaches 1 the size of the cleaning domain shrinks by half from the size when F_a/F approaches zero. Thus, in the remainder of this paper we examine the cleaning latitude not in terms of μ_{TB}-μ_{TP}, but rather in terms of the more controllable parameters such as particle size, charge, and blade load that influence F_a/F. We do this by the examination of models for the adhesion and blade forces.

III. Force Models

There are two types of forces typically considered in toner adhesion calculations, Coulomb and van der Waals. For small toner particles, below 10μ in diameter, van der Waals forces can dominate if molecularly smooth toner and substrate surfaces come in contact. If such contact does occur, van der Waals adhesion forces can approach or exceed 100 nanoNewtons. Such large forces surpass all other forces, both Coulomb and blade forces, and can render a toner uncleanable. Fortunately, this does not usually happen. Toners in general are rough enough that the resulting van der Waals forces are usually small. When the toner particles themselves are not rough, as is the case with some emulsion aggregation toners, submicron additives are usually included to enable toner flow, development, and transfer, as well as cleaning. For rough toners, and for smooth toners that have properly functioning additive packages, the van der Waals forces are typically on the order of one nanoNewton, small compared to the other forces. When toner surfaces are smooth, sometimes cleaning and transfer can be enabled via rough substrate surfaces. Below we consider both Coulomb and van der Waals forces in cleaning.

Coulomb Forces

Hays[2] has proposed a patch charge model, which places a fraction f of the toner charge adjacent to the substrate, with the remainder (1-f) on the opposite side of the particle. Within the charge patches, the charge density is assumed to be σ, created by triboelectric interactions between toner particles and carrier beads. The Hays adhesion force is:

$$F_{patch} = f\sigma q/2\varepsilon_o, \qquad (6)$$

where q is the total toner charge, f is the fraction of the charge adjacent to the substrate, σ is the charge density in the patches, and ε_o is the permitivity of free space. Eq.(6) might be expected to hold for isolated toner particles in lightly toned areas, such as image highlights. Hays[2] suggests values of $f = 0.2$ and $\sigma = 50 nC/cm^2$ as representative. Clearly, these values may vary with the choice of toner and carrier. Indeed, we would expect the coefficient f to have a statistical distribution centered around some small value, such as Hays' 0.2 suggested value. Thus, there is not a unique relation between adhesion force and toner charge or size, but rather a relation that holds over a statistical ensemble of particles.

For heavily toner image areas the adhesion force is expected to be more complicated. This is because all of the charge patches on the different toners generate image charges in the substrate. Image charges not only from the specific toner, but also from all of the neighboring toners, act to increase the Coulomb adhesion force. Such effects have been considered by Goel and Spencer[3] for uniformly charged spherical toner. T. B. Jones[4] has considered this effect within the context of the patch charge model for some specific toner spatial arrangements on the substrate surface. For a close packed toner monolayer arranged on a square grid Jones finds:

$$F_J = \frac{2\xi q^2}{\pi\varepsilon_o D^2}\left\{(1-f)f + \frac{\alpha(1-f)^2}{8} + \frac{3\sigma f}{2D\rho(q,m)} + 4(1-f)[f\Sigma_1+(1-f)\Sigma_2]\right\}, \qquad (7)$$

where $\Sigma_1 = 0.24$, and $\Sigma_2 = 0.17$, and are related to lattice sums over the square toner lattice on the surface of the photoreceptor, $\alpha = 1.22$ is the Goel and Spencer image force parameter for a uniformly particle, and $\xi = (\kappa_\sigma - 1)/(\kappa_\sigma + 1)$, where κ_s is the relative dielectric constant of the substrate, corrects the image force for a finite dielectric constant substrate. In Eq. (7) q is the toner charge, D the toner diameter, m the toner mass, and ρ the mass density of the toner material.

We see that the Jones form of the patch charge model for monolayer coverage is considerably more complicated than the Hays form for an isolated charged particle. Terms of the form q/D, D, and q/m all occur. If we expand Eq. (7) and collect terms, we find only terms of the form $(q/D)^2$ and $q=(q/D) \times D$. Thus, the Jones adhesion force can be expressed in terms of the toner particle location on a q/D versus D charge spectrum plot. Typically, charge spectra peak at approximately -0.5 fC/μ, which corresponds to adhesion forces of 20-40 nNt. Data contours extend over the range –1.0 to 0.0 fC/μ. Outside this range charge spectra are usually ignored as background. However, the high q/D background regions, beyond q/D=-1.0 fC/μ, correspond to toners with high adhesion force, in some cases as high as 100-300 nNt. These outlying toners can have adhesion forces a factor of ten higher than those toners at q/D=-0.5 fC/μ.

If we examine Eq. (7) we find that the adhesion force no longer vanishes at f=0, as does the Hays patch charge model, Eq. (6). For small f Eq. (7) approaches $\xi(\alpha + 32\Sigma_2)$ times the simple image charge force of a toner on a conducting substrate. Thus, the Jones form of the patch charge for monolayer coverage, in the limit of vanishing f, gives an adhesion force very reminiscent of that for a simple isolated image charge for a single particle, renormalized by a coefficient $\xi(\alpha + 32\Sigma_2) \approx 2.85$. Thus, for a particle in a monolayer the image force should be increased by about a factor of three over the simple image force model. High f particles can have adhesion forces much higher. While these particles are statistically unlikely, they are the statistical outliers that pose problems for blade cleaners.

van der Waals Force

There are several formulations of the van der Waals force analysis. For the discussion here we make use of that due to Johnson, Kendall, and Roberts[5]:

$$F_{eff} = F_N + (3/2)\pi D\Gamma + [3\pi D\Gamma F_N + ((3/2)\pi D\Gamma)^2]^{1/2}, \tag{8}$$

where F_{eff} is the effective normal force on the particle, F_N is the actual applied normal force on the particle in the absence of van der Waals forces. We will use the Jones form of the patch charge force, F_J, for F_N. Here Γ is the work of adhesion for the two contacting surfaces. Within this formulation the effective force on the toner is not simply the sum of Coulomb and van der Waals terms, but is a more complicated functional of the work of adhesion, particle size, and the Coulomb force.

There are several methods of obtaining the work of adhesion estimates [see discussion in Kaelble,[6] and references cited therein]. A reasonable approximation is that the work of adhesion is *twice* the geometric mean of the surface energies of the two contacting surfaces. These surface energies can be obtained from the contact angles of fluid drops on the material surfaces. For toners and photoreceptors, surface energy values lie between 20 and 40 mNt/m. Polyurethane blades have somewhat higher surface energies, 50-65 mNt/m.

The interactions between the effective normal force, the applied normal force, surface energy, and particle size has additional implications for cleaning beyond those we have space to discuss here. Kendall[7] has shown that surface energy effects increase the effective friction coefficients for small spherical particles, in some cases by up to a factor of two over the values measured for macroscopic block samples of the same materials. Meyer[8] has shown such effects also carry over to other particle shapes, such as flat particles. Clearly this can have implications for cleaning where viewed in terms of the cleaning latitude space, shown in Fig. 2.

C. Blade Force

A blade subject to a load P exerts a hydrostatic-pressure-like force on toners under the blade:

$$F_{load} = P2\pi R^2, \tag{9}$$

where P, the pressure under the cleaning blade, is given by P = Lg/w, where L (in Kg/m), g is the acceleration of gravity, and w is the nip width of the blade against the substrate. When there is isolated toner in a background region, the force is higher. To pass the blade a toner must be embedded inside the elastomer itself and roll underneath. Thus, we expect the force on the toner to be coverage dependent. Eq. (9) appears to give a reasonable description of the blade force on a *collection* of toners, and will be used here.

IV. The Latitude Space in Xerographic Coordinates

In section II we considered rolling detachment, and showed that the angle of the border of the domain for good cleaning depends on the value of the ratio of adhesion to blade force, F_a/F. We have spent the intervening section III developing models for these forces. Now it's time to put the pieces together and see what the cleaning domain border angle looks like in a xerographic parameter space. We choose to look at the force ratio in charge spectrum space, q/D versus D. This space is convenient for us because we typically measure charge spectra for new toners or new toner-carrier developer mixes in the process of evaluating them. Charge spectra data is useful because it can be reprocessed to give information in many different formats. Here we look at contours of the cleaning domain border slope, $\{[1+(F_a/F)]/2\}$, [see Eq. (4)] within the charge spectrum space. We do this for a worst-case example. We assume the toner is smooth, so that there is full toner-substrate contact. We also assume that the toner additive package has insufficient additives, so that there are toner particles that are unspaced from the substrate surface. We assume a high work of adhesion, 63 mNt/m, twice the square root of a 25 mNt/m photoreceptor surface energy, and a 40 mNt/m toner surface energy (6). The resulting cleaning border slope is contoured in Fig. 3. As we see, for large particles the slope is small, regardless of q/D. From Fig. 2 we see that this ensures a large good cleaning domain. As the particle size decreases below 3µ the slope rapidly increases, decreasing the size of the cleaning domain.

V. Discusion

The practice about ten years ago was to bottom cut toners, removing particles below about 5µ. As we see from Fig. 3, this practice removed toners likely to cause cleaning problems. However, both for reasons of toner economy, to improve image quality, and to minimize curl by minimizing the amount of toner on paper, small toners are seen as advantageous. As new blade, toner, and photoreceptor materials have become available, there has been considerable success in cleaning smaller toners.

As we see from Fig. 3, when the toner diameter decreases below about 2-3µ, contours of equal the cleaning boundary slope lie close together, indicating a rapid decrease in cleaning latitude with small changes in particle size. Indeed, for these small particle sizes the q/D of the particles becomes important. Large q/D results in larger image forces and higher adhesion. This isn't a dominant effect for the majority of toners, which have q/D's in the range –1.0-0.0. The highest adhesion (F_a/F in the range ≥1.0), or lowest cleaning latitude, occurs for q/D's more negative than q/D=-1.3 fC/µ. These toners occur in sufficiently small numbers that they don't appear on usual charge spectrum plots. However, it is these statistical outliers that are most likely responsible for cleaning failures.

This may pose a fundamental problem to application of blade cleaners with new smaller high tribo toners, and impose a limit to the image quality achievable with blade cleaners. However, Fig. 3 does not mean that blades can't clean small particles, only that the latitude is less than for larger toners. These problems can be controlled by ensuring that the van der Waals force is mediated via toner additives, by controlling the friction coefficients of blade and photoreceptor, by controlling q/D of the statistical outliers, and by controlling toner fines.

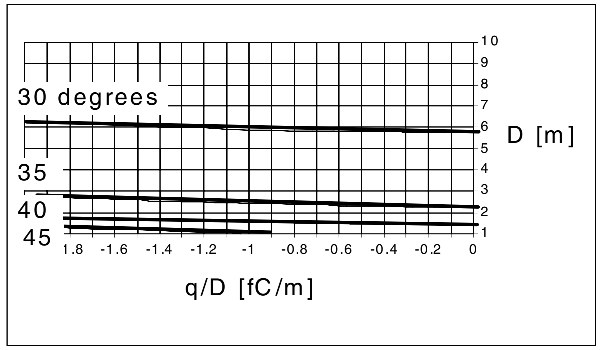

Figure 3. Contours of lower cleaning domain boundary angle in charge spectrum coordinates, for f=0.2, σ=50nC/cm², toner surface energy 40 mNt/m, and photoreceptor surface energy 25 mNt/m.

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Biography

Robert Meyer is a member of the research staff at the Wilson Center for Science and Technology, Xerox Corporation in Webster, NY. He obtained Bachelors degree in physics from Cornell University in 1971 and a Ph.D. in physics from the University of Illinois at Urbana-Champaign in 1977. Since joining Xerox in 1986 he has carried out research in the areas of cleaning, color science, development physics, and ion optics. He is a member of the American Physical Society.