Electrophotographic Printing on Textiles and Non-Planar Substrates

D. S. Rimai
NexPress Solutions, LLC, Rochester, New York, USA

D. J. Quesnel
Department of Mechanical Engineering, University of Rochester, Rochester, New York, USA

Use of electrophotographic techniques to digitally produce images on textiles and non-planar substrates can be accomplished if the adhesion forces between the toner and the photoconductor are sufficiently reduced and/or that the forces between the toner to the receiver are greater than those adhering the toner to the photoconductor.

Journal of Imaging Science and Technology 48: 10–14 (2004)

Introduction

The ability to print digitally produced images on textiles, rough graphic arts papers, and non-planar objects would greatly expand the capabilities of the graphic arts industry and would allow industries to produce custom made objects with greater facility and lower costs. In many ways, ink jet technology might appear to be the method of choice for digital printing on textiles.[1,2] This would be especially true for non-planar substrates. However, the use of electrophotographic technology has been the subject of some research[3] and has some important advantages over ink jet, especially when combining requirements of high speed processing, image quality, and image durability. However, a major impediment encountered while attempting to use electrophotographic technology to produce images on textiles is the difficulty in transferring the image from the photoconductor to the receiver. This occurs because of the presence of air gaps that are introduced when textured materials are used as receivers. For example, Chowdry[4] attempted to electrostatically transfer toner having a volume-weighted diameter of approximately 12 µm to bond paper. Using microdensitometry and profilometry, he found that the toner preferentially transferred to the peaks of the paper, with little toner transferring to the valleys. Rimai and Chowdry later found that toned images, made with 2 µm diameter monodisperse spherical toner could be transferred if the receiver was sufficiently smooth so as to eliminate air gaps.[5] Indeed, the role of paper roughness in toner transfer was clearly recognized when calendared laser bond papers were introduced in place of more conventional and rougher xerographic bond papers to facilitate transfer of smaller toner particles. To understand the role of air gaps, let us first consider the forces exerted on toner particles during transfer.

Original manuscript received April 28, 2003

Analysis of Forces on Toner Particles

Toner Transfer Across an Air Gap

First consider toner particles in contact with the photoconductor. The subject of whether van der Waals or electrostatic forces dominate the adhesion of the toner to the photoconductor remains quite controversial, as discussed by Rimai et al.[6] Suffice it to say, both types of forces contribute to toner adhesion, with the dominance of one force over the other dependent on a number of factors including toner size, presence of submicrometer particulate addenda on the surface of the toner, toner charge, the specific nature of the surface of the photoconductor, etc.[6–9] It is precisely the fact that these two forces do depend on a number of factors that makes transferring to textiles and non-planar receivers challenging but possible.

Consider the case of a spherical toner particle in contact with a photoconductor that had been illuminated to erase the residual charge. Because of the presence of both light and the charge-generated electric field, the photoconductor can be approximated as a conducting, grounded plate and the electrostatic force of attraction F_I is related to the charge q and radius R of the particle by

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

where ε_0 represents the permittivity of free space. If the charge on a toner particle is proportional to its surface area, as would be plausible for a spherical particle that has been tribocharged in the turbulent flow of a development station, Eq. (1) can be written as

$$F_I = \frac{\pi R^2 \sigma^2}{\varepsilon_0} \tag{2}$$

where σ represents the surface charge density. Under these assumptions, it is seen from Eq. (2) that the image force would be expected to vary as the square of the particle radius. It is recognized that, for nonideal particles that have become tribocharged under nonideal conditions, the contribution of the electrostatic forces might not be so simple. For example, Hays has argued that it is more likely that the charge distribution be nonuniform, in what he refers to as a charged-patch model.[10,11] Likewise, the charge on particles often does not vary quite as R^2, but rather as some other power of R.[7,9,12] However, while these details might affect certain quantitative aspects, they not alter the general discussion. Accordingly, the present discussion will be restricted to the ideal case of a uniformly charged spherical particle.

The second type of interaction that contributes to the adhesion of toner to the photoconductor is due to surface forces that originate from Lifshitz-van der Waals interactions.[13] These interactions lead to the so-called Hamaker force law[14] whereby the force of attraction originating from surface forces F_S is given by

$$F_S = \frac{A}{6 z_0^2} R \tag{3}$$

where A is the Hamaker coefficient, representative of the energetics of the system, and is proportional to the work of adhesion w_A and z_0 is the separation distance between the particle and the substrate and is typically of the order of a few angstroms. A more detailed discussion of the origins of van der Waals interactions is given elsewhere.[15] The key feature to notice is that, for the case of a spherical particle in contact with a planar substrate, surface forces vary linearly with the particle radius. As such, they decrease with particle radius at a slower rate that do the electrostatic forces and would become the dominant force of attraction for sufficiently small particles. As in the discussion of electrostatic interactions, the behavior of surface forces for nonideal particles can be more complicated. However, as before, such complications do not affect the general nature of this paper and will, therefore, be neglected at this time.

Whenever a particle is in contact with a substrate, the attractive forces generate stresses within the contacting materials. These stresses, in turn, cause strains in the materials, thereby resulting in the materials deforming. To calculate the force that is needed to be applied to detach the particle from the substrate, the work that went into creating these deformations must be taken into account. It is not correct to ignore this work and attempt to calculate the detachment force merely by balancing the attractive forces with the applied detachment force.

Johnson, Kendall, and Roberts,[16] hereafter referred to as JKR, proposed an adhesion theory, assuming small, elastic deformations, that determined the detachment force from energetics, rather than force, considerations. According to the JKR model, the adhesion induced contact radius a is related to the applied load P, the work of adhesion w_A, and the particle radius R by

$$a^3 = \frac{R}{K}\left\{P + 3w_A\pi R + \left[6w_A\pi RP + \left(3w_A\pi R\right)^2\right]^{1/2}\right\} \tag{4}$$

where

$$w_A = \gamma_p + \gamma_s - \gamma_{int} \tag{5}$$

where γ_P and γ_S represent the surface energies of the particle and substrate, respectively, and γ_{int} is the interfacial energy between the particle and the substrate. K is a factor that depends on the Young's moduli and Poisson ratios of the two materials. A more detailed discussion of the JKR theory is given elsewhere.[15]

Let us now consider the detachment of a toner particle under the influence of an external load. Since Eq. (4) represents real contact radii, it must be real. A force Π that is applied to effect detachment represents a negative load. However, the radicand cannot become negative. Accordingly, detachment occurs when

$$P = -\frac{3}{2} w_A \pi R. \tag{6}$$

In the absence of any charge, assuming a reasonable value for w_A of 0.05 J/m^2, Eq. (6) predicts that the applied force needed to detach a particle with a radius of 5 μm would be about 1200 nN. Experimentally, it has been found that the detachment force for particles of approximately this size are in the range of 300 – 1,000 nN.[7–9,11,17] The discrepancy between theory and experiment is most likely due to small asperities on the surfaces of the materials.[18,19]

To treat the electrostatic contribution rigorously in JKR theory is not simple. In principle, a force other than a surface force can be considered part of the external load. However, electrostatic forces are long-range and, therefore, would require that the JKR theory, which is derived from contact mechanics, be generalized to include long-range interactions. This is beyond the scope of this paper. However, recently Rimai et al.[7] and Hirayama et al.[8] found that simply adding the electrostatic term to the applied load was a reasonable approximation.

In general, toner transfer from the photoconductor to the receiver is accomplished by applying an electrostatic field of magnitude E_{detach}. Accordingly, toner transfer across an air gap would occur when

$$qE_{\det ach} = -\frac{3}{2} w_A \pi R - F_I \tag{7}$$

or

$$E_{\det ach} = -\frac{3w_A}{8\sigma R} - \frac{\sigma}{4\varepsilon_0} \tag{8}$$

According to Eq. (8), the field needed to transfer a toner particle decreases with increasing toner size. As stated previously, the values for nonideal toners may vary somewhat. However, the measured detachment forces for ground toner particles that are not heavily coated with silica, which serves as a release aid, are quite comparable to the calculated and measured values of spherical toners, so any discrepancy should be minimal.

The magnitude of the electric field that can be applied across and air gap is limited by Paschen discharge.[20] As seen in Fig. 1, the field that an air gap can support varies inversely with the size of the gap. With a 15 μm-size air gap, which would easily be established with a single layer of toner particles having diameters of approximately 10 – 12 μm are combined with the natural roughness of even calendared papers such as laser bond or clay coated graphic arts papers, the transfer field would be limited to approximately 35 V/μm. Assuming that the radius of the toner to be transferred is 5 μm, its mass density is 1.0 g/cm^3, its charge-to-mass ratio is 10 μC/g, and the work of adhesion is 0.05 J/m^2, the field needed to transfer this toner particle across an air gap would be approximately 230 V/μm. It would not be possible to make this toner jump across an air gap. Furthermore, higher toner stacks, such as might be present in high density regions, would increase the size of the air gap, thereby decreasing the Paschen discharge limit.

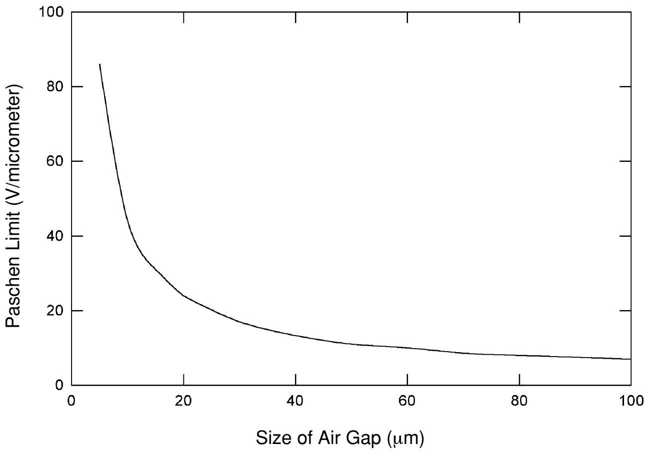

Figure 1. The Paschen limit as a function of the size of an air gap.

The problem of having toner particles transfer across an air gap is even greater when textured graphic arts papers or textile goods such as fabrics are used. Here, the air gaps can be several mils and can reduce the Paschen discharge limit to below 10 V/μm. With some fabrics, the weave is sufficiently thin so that the size of the air gap is comparable to the thickness of the fabric. This would even further reduce the Paschen discharge limit. In order to successfully transfer toner across such gaps, it would be necessary to decrease the forces of adhesion holding the toner to the photoconductor.

Toner Transfer when Toner is in Contact with the Receiver

Let us now assume that both the receiver and photoconductor are in contact with the toner particle during transfer so that there is no air gap that the toner particle must traverse. The size of the air gap in the vicinity of the toner is still determined by the roughness of the receiver and the size of the toner so that, for all intensive purposes, the magnitude of the transfer field that can be applied has not been changed. However, now there is an additional force P' acting acting on the toner particle due to the toner-to-receiver surface forces, that can also be considered part of the external load. According to JRK theory

$$F_S{}' \leq \frac{3}{2} w_A^R \pi R \tag{9}$$

where $w_A{}^R$ represents the work of adhesion between the toner particle and the receiver. In the extreme case, the toner particle would detach from the receiver and would either fail to transfer or become a satellite.[17]

For the case where the where the toner contacts both the photoconductor and the receiver, Eq. (7) can be generalized to

$$qE_{\det ach} = -\frac{3}{2} w_A \pi R - F_I + F_S{}' \tag{10}$$

or

$$qE_{\det ach} = -\frac{3}{2} w_A \pi R - F_I + k w_A^R \pi R \tag{11}$$

where $0 \leq k \leq 3/2$. Again, it should be noted that Eq. (11) is not strictly correct because it does not take into account the energy associated with the elastic strains due to the image charge induced force.

In the extreme case where $w_A = w_A{}^R$, it would only be necessary to apply a sufficient electric field to overcome the force due to the electrostatic image charge. This would explain Chowdry's[4] observations that toner transfers preferentially to the higher areas of a receiver and can explain why transfer to fabrics and textured graphic arts papers is difficult.

Transfer to Textured Papers and Fabrics

As should be apparent from the preceding discussion, transfer of toned images from a photoconductor to textured papers and fabrics is difficult for two reasons. First, the presence of area in which the toner does not contact the receiver prohibits any off-setting of the surface forces that contribute to the adhesion of the toner to the photoconductor. This means that the only force acting to detach the toner particles from the photoconductor comes from the applied electrostatic force. Second, the magnitude of the electrostatic force that can be applied is less than would be allowed in the absence of the air gaps due to the decrease in the Paschen limit with increasing air gap size.

In this study three color toned images were electrostatically transferred to textured papers and cloth. Images were made on a full process laboratory breadboard that was capable of sequentially transferring cyan, magenta, and yellow separations, in register, to a receiver.

Transfer was accomplished by wrapping the receiver around a biased transfer roller comprising an aluminum core overcoated with a polyurethane blanket having a resistivity of 9×10^{10} Ω-cm. This resistivity was chosen because it allowed transfer to occur in the so-called "constant current" mode.[21,22] As discussed elsewhere,[21,22] in this mode the transfer field is only dependent on the charge on the roller and is independent of both the thickness of the gap formed by the toner, air, and receiver, as well as the receiver resistivity and thickness. The imaging and transfer process speeds were both 13 cm/s. The transfer nip width was approximately 1 cm. Calculations[21,22] show that, for this particular roller at this process speed, the optimal roller bias is 2.2 kV. This was experimentally verified by transferring toned images to smooth clay coated papers such as Potlatch Vintage Gloss and verifying that transfer defects associated with ionization did not occur at this voltage, but did occur if the voltage was increased by approximately 100 volts.

The toners used in this study comprised a polystyrene binder, having a mass density of 1.0 g/cm^3 and either cyan, magenta, or yellow pigments. The toners were made by compounding and grinding. No silica or other particulate surface addenda was used. After grinding, the toner was classified to remove both course and fine particles. The volume-weighted average diameter of the toner was approximately 12 μm, as determined using a Coulter Multisizer. The toners were mixed with a carrier to allow electrostatic latent images to be developed using two-component development techniques. Toner charge, measured using the method described by Maher[23] was approximately 15 μC/g, corresponding to a charge per particle of 1.35×10^{-14} C.

The photoconducting imaging member was a commercially available, negatively charging composite organic photoconductor comprising a polyester binder. The surface energy of the photoconductor was initially determined by contact angle measurements using distilled H_2O and spectral grade CH_2I_2, with the interfacial energy estimated using the Good–Girafalco approximation and was found to be 45 ± 2 ergs/cm^2. This value is consistent with the surface energy of polyester and is indicative of the absence of any contamination that could serve as a release agent. For example, a photoreceptor surface contaminated with silicone oil (coating surfactant) would typically have a surface energy[24] of approximately 35 ergs/cm^2.

Cyan, magenta, and yellow separations were produced by exposing separate charged frames of the photoconductor to an appropriate test target using red, green, and blue filters. The frame containing the latent image separation was then developed by bringing the photoconductor into contact with the appropriate development station.

Roughness measurements on papers that are normally used in an electrophotographic process were performed using a Surtronic-3 profilometer with a 10 μm tip. Typical values ranged between approximately 3 μm for conventional xerographic bond papers to approximately 0.6 μm for some of the better clay coated papers such as Potlatch Vintage Gloss. Roughness measurements were not performed on the textured papers used in this study (65 lb. Navajo Fieldstone and 65 lb. Howard Felt Cover) because the resulting averages would not truly reflect the structure of the paper. Similarly, roughness measurements were also not performed on samples of cloth and on nonconventional papers such as paper towel and industrial grade toilet tissue. However, in these instances, the structure of the receiver was clearly visible to the unaided eye.

To ensure that the equipment functioned properly and that the transfer bias (2,200 volts) was chosen correctly, three color images were developed onto the photoconductor and transferred to Potlatch Vintage Gloss and xerographic bond papers in the manner previously described. The transferred images were quite smooth and uniform on the smoother, clay coated paper. However, the toner failed to transfer to the depressions in the xerographic bond paper. Although the force of adhesion was not measured for these particular toners on this particular photoconductor, Rushing et al.[17] reported a detachment force of approximately 700 nN for toners of comparable size and similar materials from a similar photoconductor. Gady et al.[25] reported a detachment force of approximately 800 nN for polyester toners with a volume-weighted diameter of 8.5 μm. As discussed by Rimai et al.,[9] the adhesion of polyester toner can be substantially higher than that of polystyrene toner. However, as also shown in the same paper, the force of adhesion increases linearly with particle radius. Thus, the smaller diameter toner used in that study would approximately offset the difference in materials. Detachment force estimates, calculated using JKR theory,[16] predict a detachment force of over 1,000 nN for this size particle. Suffice it to say, in the absence of release aids or particulate addenda on the toner, the expected force that one would need to apply to the toner particles to transfer them across an air gap would be of the order of several hundred nanonewtons, perhaps as high as 700 nN.

If the applied transfer field is limited by Paschen discharge to $3.0 - 3.5 \times 10^7$ V/m, the maximum electrostatic transfer force that can be applied to a toner particle having a charge of 1.35×10^{-14} C would be between approximately 400 – 475 nN. Naturally, there would be a statistical distribution about this force, depending on the specific charge on an individual toner particle, just as there is a statistical distribution about the force of adhesion on an individual particle. However, the force that can be exerted on such a toner particle would be, at most, comparable to, and very probably less than the force of adhesion between the toner particles and the photoconductor. This would make transfer across an air gap problematic. On the other hand, if the toner were contacting the receiver as well as the photoconductor, the contribution of the surface forces between the toner and the receiver would offset the surface forces between the toner and the photoconductor. Under that scenario, transfer could easily be accomplished. This would explain the transfer to the smooth paper and to the high spots on the xerographic bond.

To verify this hypothesis, the adhesion of the toner to the photoconductor was reduced by coating the photoconductor with a monolayer of zinc stearate. As discussed elsewhere,[6,9] this should reduce the toner-to-photoconductor adhesion to about 100 nN. The available electrostatic field should be, under those circumstances, quite sufficient to transfer toner to the elevated portions of the xerographic bond paper. Indeed, the toner was found to transfer uniformly to the xerographic bond paper in the presence of the zinc stearate.

In contrast to the relatively small air gaps presented by xerographic bond paper, the air gaps created by the textured graphic arts paper and paper toweling would be about 25 μm. This would limit the size of the electric field that could be applied to about 22 V/μm. As previously discussed, because the field was generated in the constant current mode, the size of the field was independent of the gap.

At first, the transfer roller was biased, as before, at 2.2 kV and the photoconductor coated with zinc stearate. Toner transferred well to the high spots of the paper, but not to the recesses. However, upon decreasing the voltage on the roller to 1.5 kV, corresponding to an applied field of 23 V/μm, the toner did transfer to the recesses of the various papers. This field would exert a force of about 300 nN on the toner particle, which is well in excess of the approximately 100 nN that would be needed to detach the toner from the zinc stearate coated photoconductor. Clearly, the toner could be made to jump air gaps if its adhesion to the photoconductor were sufficiently low. Moreover, it would appear that the higher voltage resulted in Paschen discharge, which may have reduced or even reversed the sign of the charge of toner on the photoconductor, thereby impeding transfer.

The ability to have the toner jump an air gap when the adhesion was reduced by coating the photoconductor with a monolayer of zinc stearate was further illustrated by transferring a colored pattern to a piece of cloth, in this case a portion of a handkerchief approximately 110 μm thick. In this case, it was, indeed, possible to transfer the toner. Upon removing the cloth from the transfer roller, toner was found to have passed through the cloth to the surface of that roller. Microscopic examination of that toner showed that it transferred in a pattern corresponding to the interfiber voids in the cloth, clearly arguing that it is possible to have the toner jump air gaps if the adhesion and applied fields are carefully controlled.

Transfer to Nonplanar, Electrically Insulating Objects

Transfer to nonplanar, electrically insulating objects poses certain atypical problems. Of these, the difficulty that would be encountered attempting to apply an electrostatic transfer field is, perhaps, the most challenging. In this case, Eq. (11) reduces to the relationship

$$\frac{3}{2} w_A \pi R + F_I \leq \frac{3}{2} w_A^R \pi R \qquad (12)$$

In this instance, as is apparent, it is vital that $w_A^R > w_A$ if the toned image is to be transferred from the photoconductor the to receiver, as F_I always attracts the toner to the photoconductor and there is no applied electric field to enhance transfer.

The imaging process and materials used in this study were very similar to those used in the study of transfer to textured receivers above, with the following exceptions. Imaging was done using black toner only instead of cyan, magenta, and yellow primaries. Imaging was done on small (12.5 × 20.0 cm) sheets of a photoconductor that could readily be removed from the imaging breadboard. Cylindrical receivers comprising glass and polystyrene beakers, polypropylene syringes, and ceramic mugs served as receivers. Finally, transfer was accomplished by removing the photoconductor from the imaging breadboard, placing it on a table, and rolling the receivers by hand over the toned image. Fusing was accomplished by exposing the image-bearing receiver to CH_2Cl_2 vapors.

In each instance, transfer would only occur if the photoconductor was first coated with zinc stearate prior to imaging. When coated, transfer was fairly complete, although some fringe areas at the edges of alpha-numeric lines were often left behind.

Upon fusing, the images were made fairly permanent, which is to say that they could be removed by abrasive rubbing, but seemed to stand up to normal handling reasonably well. This was even true for the polypropylene syringes that had surface energies, measured using so-called "dyne solutions", in the range of approximately 30 – 35 ergs/cm^2. It is, perhaps, interesting to note that, upon exposure to a plasma discharge, the surface energy of the syringes increased by approximately 10 ergs/cm^2. However, this appeared to have little affect on either transfer or fusing. However, insofar as the surface energy of one surface is just one of three components comprising $w_A{}^R$, perhaps it is not totally surprising that the transfer and fusing properties would be relatively insensitive to a small change in the surface energy of the receiver.

Conclusions

In many, if not most, electrophotographic applications, toner transfer results from a combination of balancing the adhesion forces between the toner to the photoconductor with those between the toner to the receiver. The applied electrostatic field, then, is used to apply whatever extra force is needed to detach the toner from the photoconductor. When imaging on textured materials or fabrics, establishing such a balance is often not possible because of the presence of macroscopic air gaps caused by the texture of the receiver. Even so, transfer of toned images to textured materials and nonplanar substrates is quite feasible. It appears that, in order to successfully transfer to textured materials, it is important to limit the toner adhesion to the photoconductor to a level such that the applied electrostatic transfer field can detach. In addition, it also appears necessary to control the applied electrostatic field to avoid Paschen discharge. When transferring toned images to electrically insulating, nonplanar objects, it appears necessary that $w_A < w_A{}^R$.

References

1. W. C. Tincher, Ink Jet Resin-Pigment Printing on Silk Fabrics, *IS&T's NIP 15: International Conference on Digital Printing Technologies*, IS&T, Springfield, VA, 1999, p. 200.
2. H. Park, W. W. Carr and J. Zhu, Interactions of a Single Ink-Jet Droplet with Textile Printing Surfaces, *IS&Ts NIP 17: International Conference on Digital Printing Technologies*, IS&T, Springfield, VA, 2001 p. 438.
3. W. W. Carr, F. L. Cook, W. R. Lanigan, M. E. Sikorski, and W. C. Tincher, *Textile Chem. Color.* **23**, 33 (1991).
4. A. Chowdry, unpublished results.
5. D. S. Rimai and A. Chowdry, US Patent 4,737,433 (1988).
6. D. S. Rimai, M. Ezenyilimba, W. K. Goebel, S. Cormier, and D. J. Quesnel, *J. Imaging Sci. Technol.* **46**, 200 (2002).
7. D. S. Rimai, P. Alexandrovich and D. J. Quesnel, *J. Imaging Sci. Technol.* **71**, 1 (2003).
8. J. Hirayama, T. Nagao, O. Ebisu, and I. Chen, *J. Imaging Sci. Technol.* **47**, 9 (2003).
9. D. S. Rimai, D. J. Quesnel, L. P. DeMejo, and M. T. Regan, *J. Imaging Sci. Technol.* **45**, 179 (2001).
10. D. A. Hays, in *Fundamentals of Adhesion and Interfaces*, D. S. Rimai, L. P. DeMejo, and K. L. Mittal, Eds., VSP, Utrecht, 1995, pp. 61–72.
11. D. A. Hays, in *Advances in Particle Adhesion*, D. S. Rimai and L. H. Sharpe, Eds., Gordon and Breach, Amsterdam, 1996, pp. 41–48.
12. P. Alexandrovich, unpublished results.
13. E. M. Lifshitz, *Sov. Phys. JEPT* **2**, 73 (1956).
14. H. C. Hamaker, *Physica* **4**, 1058 (1937).
15. D. S. Rimai and D. J. Quesnel, *Fundamentals of Particle Adhesion*, Global Press, Moorhead, MN, 2001. Available from the Adhesion Society.
16. K. L. Johnson, K. Kendall and A. D. Roberts, *Proc. Roy. Soc. London, Ser. A* **324**, 301 (1971).
17. A. J. Rushing, R. D. Fields, D. S. Rimai, and A. Hoskins, *J. Imaging Sci. Technol.* **45**, 187 (2001).
18. D. M. Schaefer, M. Carpenter, B. Gady, R. Reifenberger, L. P. DeMejo, and D. S. Rimai, *J. Adhesion Sci. Technol.* **9**, 1049 (1995).
19. K. N. G. Fuller and D. Tabor, *Proc. Roy. Soc. London, Ser. A* **345**, 327 (1975).
20. F. Paschen, *Wied. Ann.* **37**, 69 (1889).
21. M. C. Zaretsky, *J. Imaging Sci. Technol.* **37**, 187 (1993).
22. D. S. Rimai, D. S. Weiss, and D. J. Quesnel, *J. Adhesion Sci. Technol.* in press.
23. J. C. Maher, *IS&T's Tenth International Congress on Advances in Non-Impact Printing*, IS&T, Springfield, VA, 1994, p. 156.
24. D. S. Rimai, unpublished results.
25. B. Gady, D. J. Quesnel, D. S. Rimai, S. Leone, and P. Alexandrovich, *J. Imaging Sci. Technol.* **43**, 288 (1999).