Electrostatic Printing on Textiles and Non-Planar Substrates

David S. Weiss, Donald S. Rimai* and David J. Quesnel**, *NexPress Solutions LLC, 2600 Manitou Road. Rochester, NY 14624 and the **University of Rochester, Rochester, NY 14627*
donald_rimai@nexpress.com, (585) 613-2047

Introduction

Present day understanding of the adhesion of particles to surfaces in general and toner particles to photoreceptors in particular is based on the theory proposed by Johnson, Kendall, and Roberts [1], hereafter referred to as the JKR theory. According to that theory, the contact radius a between a toner particle and a photoreceptor is related to the toner radius R, the work of adhesion w_A, and the applied force P by

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

where K is a function of the Young's moduli and Poisson ratios of the particle and the substrate.

It is not necessary, according to the JKR theory, that the externally applied load and the adhesion forces both be in the same direction. Rather, one could exert a negative load, as would be the case, for example, of the applied electrostatic force exerted during the toner transfer process. Under these circumstances, the contact radius would monotonically decrease with an increasing magnitude of the electric field. However, since eqn. 1 represents a real contact radius, its solutions must be real. Accordingly, the radicand cannot be negative and the toner particle separates from the photoreceptor when

$$P = -\frac{3}{2}w_A\pi R \cdot \qquad (2)$$

Strictly speaking, eqn. 2 presupposes that the external load is generated via contact mechanics, *i.e.* generated by some sort of probe attached directly to the particle, such as would be the case if the particle were attached to an AFM cantilever. Applied loads that exhibit long-range interactions, such as those generated by electrostatic interactions, are not considered. Moreover, eqn. 2 does not consider the case in which at least a component of the detachment force is generated by an adhesive force applied to the particle by the contact of that particle with a second substrate.

The limitations imposed by eqn. (2) to the understanding toner transfer are clearly exemplified in electrophotography. Here, electrostatically charged particles, typically having a radius of approximately 5 μm, are transferred from a photoreceptor to paper upon application of an electric field.

The surface of most papers is rough, having a surface average roughness of the order of the diameter of a toner particle. In his toner transfer studies, Chowdry [2] noted that toner transferred readily to the high spots of the paper, but failed to transfer to the low spots. At that time, there was a perception that, for reasons that were not fully understood, it would not be possible to electrostatically transfer toner particles that had a radius less than approximately 6 μm. Subsequently, Rimai and Chowdry [3] reported that highly efficient electrostatic transfer of toner particles with a radius of 1.0 μm could be accomplished if the toner particles were monodisperse and the receiver (*e.g.* the paper) was extremely smooth. They proposed that surface forces between the particles and the receiver partially offset those between the particles and the photoconductor. The applied electrostatic force then merely needed to overcome the difference in adhesion forces rather than the total adhesive force bonding the particles to the photoconductor. In the present paper, the role of balanced and unbalanced surface forces are discussed.

Experimental

The photoreceptor used in this study comprised an organic photoconductor [4] on a nickelized poly(ethylene terephthalate) support. The nickel allowed the photoreceptor to be properly grounded. In some instances, the photoreceptor was first coated with a thin film of zinc stearate to reduce adhesion. The photoreceptor was uniformly charged and then image-wise exposed to produce an electrostatic latent image. Irregularly-shaped toner particles, produced by grinding and having a radius of approximately 6 μm, were then image-wise deposited onto a photoreceptor using magnetic brush development. The charge-to-mass ratio of the particles was measured using the technique of Maher [5] and found to be 15 μC/g, corresponding to a charge per particle of 1.35×10^{-14} C. Prior to transfer, the photoreceptor was exposed to light to neutralize any excess residual charge and to ensure that the photoreceptor could be treated in the analysis as a grounded metal plane with a charge located a distance R from its surface.

The toner particles were transferred to the receiver upon application of an electrostatic field. That field was applied by sandwiching the receiver between the grounded photoreceptor and a biased roller comprising an aluminum core and a polyurethane coating approximately 0.5 cm thick. The resistivity of the polyurethane was approximately 9×10^{10} Ω-cm. This resistivity was chosen to ensure that the field was established under constant current, rather than constant voltage conditions, thereby making the field independent of the size of any air gap or receiver thickness or resistivity [6]. Electric fields imposed on the particles were chosen to be as high as possible, subject to not exceeding the Paschen discharge limit for air prior to transfer.

A variety of receivers were used in this study. These included very smooth clay coated graphic arts papers, xerographic bond papers, and textured graphic arts papers. In addition various household items such as wood veneers, paper towels, and cloth were also used as receivers. The variations in roughness allowed various size air gaps to be established, thereby facilitating the determination of balancing the surface forces holding the particles to the photoconductor with those holding the particles to the receiver.

Results and Discussion

In the absence of any release aid on the surface of the photoreceptor, it was found that, upon application of the electrostatic field, the toner transferred efficiently and uniformly to the smooth receivers. However, toner only transferred to the high spots of the textured receivers, similar to the earlier results of Chowdry [2]. However, if the surface of the photoreceptor was first coated with a thin film of zinc stearate prior to development, toner adhesion was significantly reduced [7] and the toner could also be transferred to the valleys of the receiver. Moreover, with the zinc stearate coated photoreceptor, transfer of the particles to the peaks of the receiver, but not the valleys, occurred merely upon application of the transfer roller pressure even in the absence of any applied field. This did not occur in the absence of zinc stearate.

These results can be understood by considering all the forces acting on the toner particles. The first, of course, is the surface forces between the toner particles and the photoreceptor. In addition, there is an electrostatic image force. Since the photoreceptor was erased prior to the transfer process, this force can be approximated, using the method of images for a uniform spherical charge distribution, as a charge located a distance R from the surface of the photoreceptor, where R is the toner radius. Accordingly, the image force F_I is given by

$$F_I = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{(2R)^2} = \frac{\pi R^2\sigma^2}{\varepsilon_0} \tag{3}$$

where σ is the surface charge density of a toner particle and ε_0 is the permittivity of free space. There is also an image charge force between the receiver and the toner particles, but, for insulating receivers, are significantly smaller than they would be for a conductor and are, therefore, ignored.

There is also an applied electrostatic detachment field E_{detach}, generating a force on a toner particle qE_{detach}, where q represents the charge on a toner particle. It should be noted that nonuniform charge distributions on the surface of the toner particles would not affect the electrostatic detachment force. This is because the applied field is uniform and nonuniform charge distributions would give rise to dipoles and higher order moments. These result in forces that are proportional to the gradient or higher order derivatives, respectively, of the field. In the case of a uniform field, these terms are all zero.

Finally, if a toner particle is in contact with the receiver, there is a surface force $F_S{'}$ between that particle and the receiver that is related to the work of adhesion w_A^R between the toner and receiver. This force must be less than the force needed to remove the toner from this surface or

$$F_S{'} \le \frac{3}{2} w_A \pi R \cdot \tag{4}$$

If these forces are assumed to act as components to the total external load of the JKR model, then

$$qE_{detach} = -\frac{3}{2} w_A \pi R + k w_A^R \pi R - \frac{\pi R^2\sigma^2}{\varepsilon_0} \tag{5}$$

where k ranges in value from 0 (no contact with the receiver) to 3/2 (the bonding of a toner particle to the photoreceptor is sufficiently strong so as to detach the toner particle from the receiver).

Now let us consider the case where there is no applied field. In this instance, the toner can only be transferred to the receiver if

$$\frac{3}{2} w_A^R \ge \frac{3}{2} w_A + \frac{R\sigma^2}{\varepsilon_0} \,. \tag{6}$$

This is the case when zinc stearate has been applied to the photoreceptor, but not in the absence of zinc stearate.

Conversely, let us now consider the case in which the particle does not contact the receiver. Here, $k = 0$ and the applied electrostatic force must be able to overcome both the surface and image charge forces. This can be demonstrated experimentally in the presence of zinc stearate, but not in its absence. This accounts for the failure to transfer the toner to the valleys of the receiver unless the zinc stearate coating is present. It should be noted that, because of the limitations imposed by the Paschen discharge limit, the applied field cannot be arbitrarily increased in order to induce transfer.

It is also worthwhile to consider the effects of toner charge on transfer. While both the applied electrostatic force and the image force increase with increasing charge, the applied force increases linearly while F_I increases quadratically. Accordingly, there is an optimal value for σ to facilitate transfer.

Finally, let us consider an alternative theory of particle adhesion, originally proposed by Hays and Wayman [8], in terms of the present results. According to this theory, assuming a uniform charge distribution for irregularly-shaped, electrostatically charged particles would grossly underestimate the true electrostatic image force. Rather, adhesion is a result of image forces between localized charged patches on the surface of a toner particle and the photoreceptor. These patches occur as a result of the irregular shape of the particles precluding certain recessed areas of the surface of the particles from contacting other materials and becoming tribocharged. In other words, only the peaks of the toner particles can become electrically charged. The presence of such charged patches would allow the image charge to appear to be much closer to the surface of the photoreceptor, thereby increasing the role of electrostatic attraction in the adhesion of a toner particle.

If the image force predicted by the charged patch model is the dominant interaction, as opposed to van der Waals forces, for particles with this radius it should be possible to offer an alternative explanation to the one presented herein to explain the present experimental results in terms of the charged patch model. First let us consider the role of zinc stearate.

As previously discussed, zinc stearate is known to reduce particle adhesion. The only way this could be accomplished according to the charged patch model would be for the zinc stearate to reduce or redistribute the charge on the toner particles deposited on the photoreceptor. This would affect both the number of particles deposited and their charge. Both previous [7] and present experimental results have failed to turn up any such effects. In addition, considering the turbulence that occurs during magnetic brush development, those areas of the toner particles that can become electrically charged have done so. Any significant redistribution of charge due to the presence of the zinc stearate on the photoreceptor is unlikely.

It is also not obvious how the charged patch model could account for the toner particles not being able to traverse an air gap in the absence of zinc stearate. One might argue that the space between the receiver and photoreceptor is wider in the regions of the receiver valleys and, therefore, the fields are lower. However, as previously discussed, but operating in a constant current mode, the field would not depend on the spacing, but only on the charge present.

Conclusions

The surface forces which adhere electrically charged toner particles to a photoreceptor can be offset by contacting the opposite side of the toner particles with the receiver. This balancing of surface forces allows electrostatic transfer of charged particles from the photoreceptor to the receiver to be accomplished, even if it is not possible to apply a sufficiently strong electric field to detach the toner particles from the photoreceptor into the air. These results can be explained in terms of the JKR theory if the image charge induced forces, the applied electrostatic force, and the surface force from a contacting substrate are considered to comprise the externally applied load.

Acknowledgements

The authors would like to thank Dr. Tom Tombs for useful comments.

References

1. K. L. Johnson, K. Kendall, and A. D. Roberts, Proc. R. Soc. London, Ser. A **324**, 301 (1971).
2. A. C. Chowdry, unpublished results (1981).
3. D. S. Rimai and A. Chowdry, "Electrostatographic Method of Making Images", U. S. Patent #4,737,433 (1988).
4. P. M. Borsenberger and D. S. Weiss, *Organic Photoreceptors for Xerography*, Marcel Dekker, New York (1998).
5. J. C. Maher, *IS&T's Tenth International Congress on Advances in Non-Impact Printing*, 156 (1994).
6. M. C. Zaretsky, J. Imag. Sci, Technol. **37**, 187 (1993).
7. D. S. Rimai and D. J. Quesnel, J. Adhesion **78**, 413 (2002).
8. D. A. Hays and W. H. Wayman, J. Imag. Sci. **33**, 160 (1989).

David S. Weiss is a Scientist Fellow at NexPress Digital LLC in Rochester, New York. He received his Ph.D. in Chemistry from Columbia University (New York) in 1969. His work focuses on electrophotographic technologies with emphasis on organic photoreceptors. He is co-author of *Organic Photoreceptors for Xerography* (Marcel Dekker, Inc., 1998). He has been an Associate Editor of JIST since 1988 and served as NIP 17 General Chair. In 1999 he received the Carlson Memorial Award and in 2004 he was named a Senior Member of the IS&T.