Toner/Transfer Member Adhesion Response to Environment-Induced Material Property Changes, and Their Impact on Transfer Fields

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Abstract

Toner adhesion to substrates has been demonstrated to be a strong function of temperature. Previous work has suggested that particle deformation due to surface forces increases with reduced material stiffness at higher temperatures, thus increasing contact surface area and increasing adhesion. Toner Storage and Loss Modulus were measured for a variety of toners both on the individual toner scale and on the macro scale. These measurements showed material property changes in the region below the glass transition temperature that could account for the measured increase in toner adhesion. Toner adhesion measurements were then reconciled with transfer field forces to reveal an interaction between transfer fields, stored energy, and toner adhesion.

Introduction

Toner adhesion to substrates is higher when ambient temperatures are higher. This has been demonstrated by adhesion testing of toner and in modeling of fields from experimental printing systems. Adhesion testing of toner [1] revealed a relationship between toner charge, temperature, and adhesion of toner to be a function of the charge cubed. The hypothesis, based on the particle physics work of Jurgen Tomas [2], was that the deformation based on slight changes in modulus of elasticity of toner interacted with charge-based Coulomb attraction and increased the contact area for elevated temperature toner. The amount of increase in adhesion for toner at the warm end of many printer operating ranges was approximately double that from the cold operating ranges, depending on toner charge (Figure 1). Toner transferred onto an intermediate member in an environment at 24°C to 32°C (75°F to 90°F) had adhesion values in the 250nN range, whereas the same toner with the same charge at 15°C (60°F) had measured adhesion values in the 150nN range. The result of higher toner adhesion is that print quality degrades with increasing environmental temperatures.

There are two significant aspects of this hypothesis and the associated measurements that have yet to be addressed. First is whether material properties of micron scale toner do behave in such a way as to have the necessary changes in contact area predicted by the measurements. Second, how to reconcile the measured adhesion of toner, which is consistent throughout the literature in the 100's of nN range, with the fact that transfer fields and toner charge should only result in a force to transfer in the low 10's of nN range – and yet toner transfers.

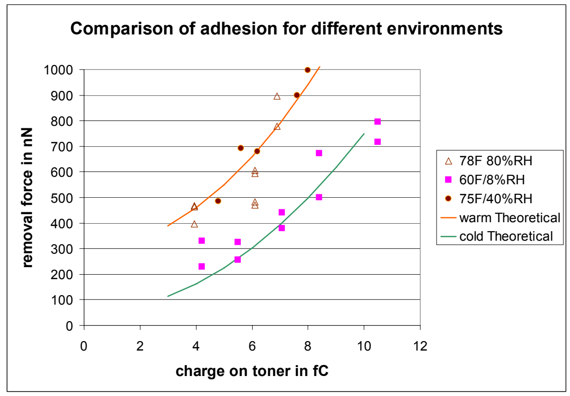

***Figure 1**. Measured adhesion for 50% removal of cyan polystyrene toner from a transfer belt at different charges and temperatures. The theoretical equation has an offset deformation (van der Waals), a q term from non-uniform charge, a Coulombic q^2 term, and a q^3 term predicting an interaction between particle deformations due to a charge induced Coulomb force and material properties which are a function of temperature.*

Temperature-Induced Changes in Contact Area

In 2011 we hypothesized that higher adhesion with increasing temperature is the result of the elastic modulus of the toner decreasing and thereby increasing the area of contact to the relevant substrate [1]. Adhesion of toner to substrates is known to be a strong function of contact area and this has been demonstrated by Law et al. [3], Rimai et al. [4, 5], and Schein [6] among others who have shown that extra particulate additives greatly decrease toner adhesion by decreasing contact area between toner and substrate. For particle physics considerations the gravitational force pulling particles to substrates is negligible but the charge related forces are significant. The gravitational force on a 6µm toner particle is roughly 0.0013nN, where as the dielectric pull from a -20 µC/g, 6µm diameter toner particle on a substrate would be 17nN which is much more significant and is therefore the key contributor to the footprint of the toner on the substrate. Deformation of a particle toward a substrate to which it is adhered is a function of the charge on that particle [7, 8, and 9] and the dielectric properties of the substrate. The adhesion measured by rolling resistance is a function of the normal force to the 3/2 power. Inserting a charge squared term for normal force yields a pull off force that is sensitive to the charge of the toner cubed. This q^3 term ends up being extremely significant in the adhesion equation, accounting for up to half of the adhesion measured (Equation 1).

$$\mathbf{F_a = A + Bq + Cq^2 + Dq^3} \qquad (1)$$

Where:

- A represents the Van der Waal's attraction forces
- Bq represents the additional force due to non-uniform charges [10]
- Cq^2 represents the actual Coulombic attraction arising from multiple particles
- Dq^3 represents the Van der Waal's attraction that is a function of the toner footprint from the Coulombic attraction forces

However, the question remains as to whether material property changes are significant enough to result in this amount of contact area difference.

To address this question, two sets of material property measurements were completed to understand the sub-Tg response of toner to temperature. One set of experiments was carried out by Hysitron Corporation on two samples of cyan toner: a polystyrene base CPT and a polyester based CPT. The same measurements, on the same toner samples, were completed on macro-molded samples at Lexmark International. Macro-scale and nano-scale measurements compared favorably. The measurements on the toners were indentation testing and DMA testing. Nano-scale measurements on individual toners compared fairly well with macro-scale measurements on bar samples. Nano-DMA for a polystyrene toner gave a Tan-Delta of 0.025-0.030 for a room temperature measurement while the macro-DMA on the same material extruded into a bar gave 0.037 for about the same temperature. Both systems gave a Tan-Delta of 0.040 for 38°C (100°F) (Figure 2). Young's Modulus alone could only account for a 7% increase in contact area across the temperature range.

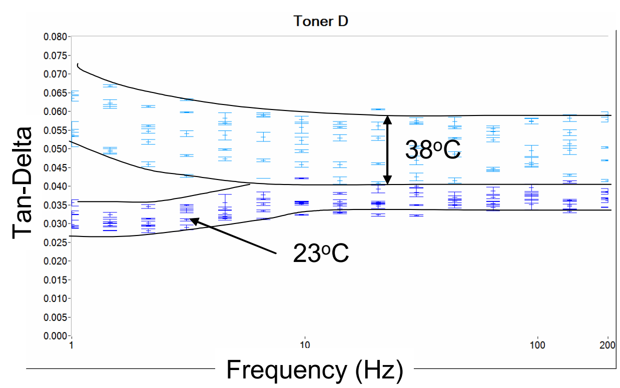

***Figure 2**. Tan-Delta measurements for a polyester toner at two different temperatures. Loss Modulus increases as temperature increases*

Alternatively**,** the storage and loss modulus of toner do respond more strongly to temperature, exhibiting varying degrees of viscoelasticity. Toner at 38°C (100°F) responded with a higher tan-delta indicating a much higher level of energy lost. This increase in Loss Modulus to Storage Modulus was about 1/3 depending on sample and frequency (Figure 3)

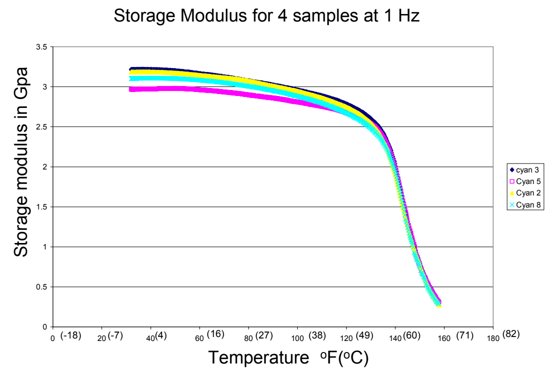

***Figure 3**. Storage modulus for cyan polystyrene toner as a function of temperature. The measurements used were changes between 60°F and 90°F.*

Transfer fields are approximately 5 times as strong as Coulomb image fields. The proposed new model is that toner deforms under the short-duration impact of a transfer field temporarily increasing contact area. Warm toner loses a large amount of its ability to rebound from such deformation and remains with a higher contact area after the transfer event. Toner in a color printer, which must endure multiple transfer field "bumps," is deformed even further. As the toner on the intermediate member approaches a second transfer station and needs to be electrostatically removed, its contact area has been increased by a loss-deformation as well as an image-force induced deformation which has both elastic and plastic components. The actual increase in contact areas are is quite small for both warm and cold situations. The radius of contact for a 16°C (60°F) toner only under Coulomb attraction force should be around 0.013µm. Under the additional load of a transfer field, contact radius will climb to 0.017µm. If a warm toner particle undergoes two or more transfer fields the contact area could easily remain at 0.020µm entering 2nd transfer. The associated adhesion forces would be 147nN for the cold toner at 2nd transfer and 226nN for the warm toner of the same charge at 2nd transfer. These numbers are very close to the predicted values from the measured adhesion.

Reconciling Adhesion and Transfer fields

If adhesion values are indeed in the 100nN range with higher values for warm toner, how is it possible that any significant amount of toner transfers at a second transfer step? The theoretical limit for field between two parallel plates before Paschen breakdown is -7.5E7V/m [11]. Electrophotographic systems consist of rollers and belts which are less perfect than infinite parallel plates. Analytical modeling, calibrated to actual printers, shows transfer fields actually achieve high transfer efficiency for 6 micron diameter, silica-covered toner when the field is around - 5E6 V/m. By the time the field reaches -1E7 V/m, many systems are experiencing unacceptable Paschen breakdown. A field of -5E6 V/m can only exert of force of around 30nN on toner, a force roughly equivalent to the image field holding it to the transfer belt or photoconductor.

It has been suggested [4] that mechanical contact with the final media is a requirement for good transfer, allowing van der

Waals attraction to the receiving media to make up for what is lacking in electrostatic force from the donating member. Mechanical contact with a substrate assists only a fraction of the toner involved and is not sufficient to get the high transfer efficiencies demanded by today's printing systems. SEM images show the roughness of paper fibers dwarfs toner sizes (Figure 4). Transfer efficiency testing shows that over 90% of toner actually transfers in this situation. This suggests that a large portion of the toner will transfer to a media based on electrostatic forces alone.

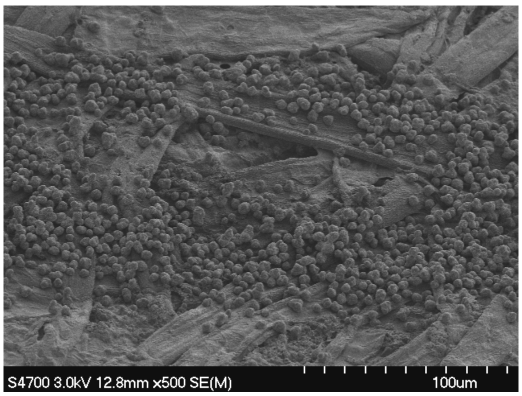

***Figure 4**. Scanning Electron Microscope image of unfused toner transferred onto a bond paper. Toner size is dwarfed by feature size in the paper, making it necessary for toner to "jump" to transfer with high efficiency to the paper.*

The answer lies in the understanding of energy stored in deformation of the toner. When a toner deforms under an electrostatic field, part of the deformation is plastic and part is elastic. There is some plastic deformation even for the coldest particle and more for the warmest. When toner on an intermediate member enters a second transfer field, the superposition of the fields relaxes the dielectric polarization thus reducing the image force between toner and substrate. Freed of this image force, the energy stored as elastic deformation is gently released and the toner rebounds, leaving only the plastic portion to create an adhesion force holding toner to substrate (Figure 5).

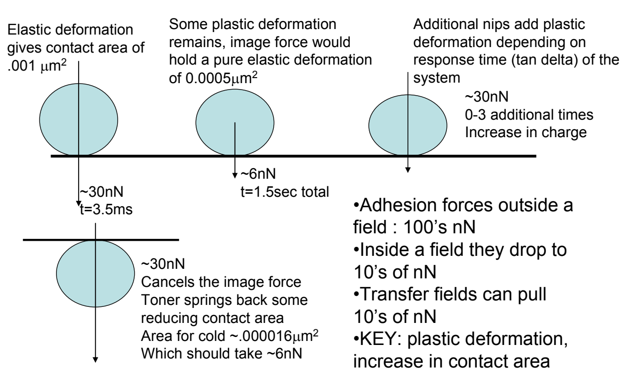

***Figure 5**. Toner contact area to the transfer belt changes as a function of the external field. Loss Modulus of the material determines how much of the deformation is plastic, permanently increasing contact area and adhesion.*

For a cold toner particle, the plastic deformation is small and the toner releases with only a few nN of force. For warm toner, the remaining contact area is higher. Using the proportions suggested by DMA measurements, a toner that was deformed to 0.020μm contact radius may only spring back to a contact radius of 0.013μm. This would take a removal force of about 79nN or a transfer field of -1.6E7V/m, more difficult, but possible.

Conclusion:

The critical components to adhesion of toner to a substrate are a combination of toner charge and contact area which is determined by particulate coverage, the sequence and duration of electrostatic fields from downstream nips, and the relaxation time of the toner. Both macro and nano-scale measurements of toner properties demonstrate these relationships. Based on estimates of toner properties, contact areas between toner and substrate were predicted for different toner types and temperatures, as well as their impact on resultant adhesion. Adhesion forces were reconciled with transfer forces and SEM images to show a physical model that works for a transfer system.

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