Measurements of the Effective Dielectric Thickness of Toner Layers in Transfer Systems

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Abstract

The "effective dielectric thickness" of toner layers, $D_{\text{eff toner}}$, is an important physical parameter that affects the electrostatic field in a transfer nip. This parameter is also an indicator of the compactness of toner piles, which affects toner cohesion and adhesion as well as air breakdown within a photoconductor and a paper sandwich. This paper presents measurements of the effective dielectric thickness introduced by toner layers under various pressures. Possible implications of our results to transfer sub-system are discussed.

Introduction

In many situations in transfer there is a tendency for the toner receiving substrate (paper, etc.) to be essentially at an equipotential over an extended region above the toner image. One example is a biased transfer system and another is a corotron transfer system under conditions of high paper moisture content where lateral conduction mechanisms are dominant. The applied transfer field in this case is inversely proportional to the sum of the dielectric thickness of the insulating layers between the biased layers of the toner receiver and the photoconductor substrate.[1,2,3]

$$E = V/\Sigma D_i \qquad (1)$$
$$D_i = d_i / \kappa_i$$

Where V is applied voltage, D_i and d_i are the dielectric thickness and the thickness of ith insulating layer respectively, and κ_i is the dielectric constant of ith layer.

Within a toner receiving and a deposition plate sandwich, many factors such as cockled paper, high toner pile images next to low pile images or background, or toner image topography introduced by toner size distributions or by the development system[4] could all introduce air gaps into a transfer zone. The combination of the toners and air gaps between the toner developing plate and the receiving plate, divided by the effective dielectric constant of the layer, will be referred to as the effective dielectric thickness of the toner layer ($D_{\text{eff toner}}$). In color systems where there will be single and multiple color layer combinations in image regions, there can conceivably be a large range of toner dielectric thickness for various colors, and the affect of $D_{\text{eff toner}}$ variation on the local transfer fields acting on the various colors can be large. An understanding of the range of dielectric thickness introduced into a transfer system vs. the developed toner mass per unit area (DMA) is therefore of interest.

Measurement of the effective toner dielectric thickness is of potential interest for other reasons. In electrostatic transfer even relatively small air gaps between the substrate and toner, or within the toner pile itself, will limit the transfer field due to Paschen air breakdown.[4] To obtain high efficiency toner transfer one has to reduce the air gaps to enable high fields without causing air breakdown, or one has to minimize the adhesive forces between the toner and photoconductor such that moderate fields below the Paschen limit can transfer most of the toner. Generally, a combination is required. Mechanical pressure is typically introduced into a transfer design to suppress air gaps. Pressure on a toner pile can increase the contact area between toners or between the toners and other surfaces, and can thus affect toner cohesion and adhesion. Discussion of the impact of pressure on adhesion and cohesion is beyond the scope of this paper, but measurements of the effective toner dielectric thickness vs. pressure are used to begin to understand the underlying toner packing mechanisms that will influence the transfer field as well as toner adhesion and cohesion.

Experimental Details

Figure 1 shows a schematic of a pressure cell. The toner deposition plate contains an electrically isolated region that will be referred as a field probe. The probe was formed by epoxying an anodized aluminum disk with a diameter of 3/4″ into a slightly oversized hole in the aluminum plate. The insulating layer (anodized layer plus glue) surrounding the probe was thick enough to insure electrical isolation from the rest of the plate but was thin enough to avoid significant toner deposition variation across the insulating layer. The plate with the isolated field probe was polished flat with a wet polishing method and then covered with a thin insulating kapton tape. As described shortly, the field probe was used to determine the toner dielectric thickness. In measurements, uniform solid area toner images were developed onto the toner deposition plate by mounting the plate on a cantilever that was moved through a development housing at a controlled speed. Simple biased development was used and the DMA was controlled by the applied bias and the plate moving speed. The developed mass/area was measured with a precision balance.

As shown in Figure 1, the pressure cell contains a toner receiving plate against the toner deposition plate. The hydrostatic pressure was applied to the receiving plate and the magnitude of the pressure was monitored with pressure gauges. The receiving plate contains a 3 mm conformable layer of silicone foam material (effective durometer of ~20) to insure a reasonable degree of uniformity on a macroscopic scale of the applied pressure on the toner layers. This foam layer simulates a typical pressure situation that might be present in, for example, a biased transfer system.

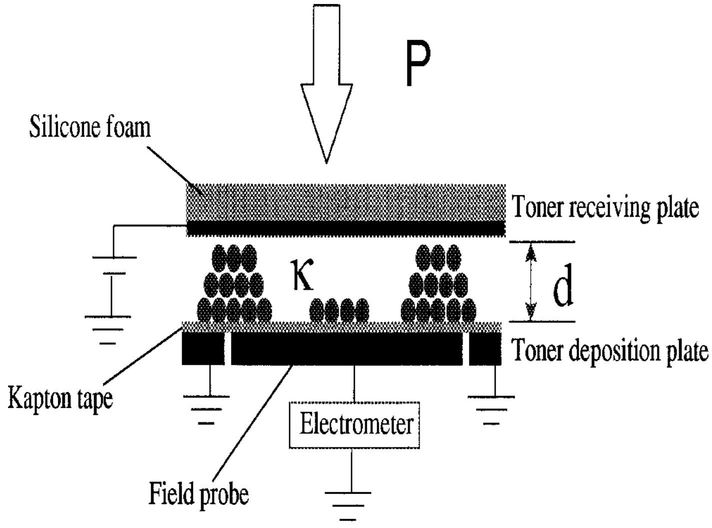

Figure 1. A schematic of a toner receiving plate, toners, and a toner deposition plate containing a field probe. The field probe is used to measure the average effective dielectric thickness of the toner layers $D_{eff\ toner}$, defined as the toner thickness (d) divided by the effective dielectric constant of toner (κ).

The actual toner receiving substrate that contacted the toner layer was bonded to the foam. In one set of experiments a 0.5 mm thick microporous conformable conductive foam film (~ 0.75 micron pores, effective durometer ~ 10, resistivity less than 10^4 ohm-cm) was used. In another set a much less conformable titanium coated mylar film was utilized.

The toner developing and receiving plates form a parallel capacitor. The effective dielectric thickness of the toner, $D_{eff\ toner}$, is calculated from the capacitance,

$$C = \varepsilon_o A/(D_{eff\ kapton} + D_{eff\ toner}) \qquad (2)$$

where A is the area of the probe and Deff kapton stands for the effective dielectric thickness of the kapton tape. To measure the capacitance of the parallel capacitor, the field probe was connected to a Keithley 617 electrometer operated in the coulomb mode and a potential of 100 volts was applied to the conductive receiver ($C = Q/V$). The term $D_{eff\ kapton}$ is a constant in the experiment and was measured with zero toner coverage. The measurements of $D_{eff\ toner}$ as a function of the applied pressure were performed for a range of developed mass/area. Magenta polyester toner with an average diameter of 7 µm and mass density of 1.17g/cm^3 was used in this study.

Experimental Results

Figure 2 displays representative plots of $D_{eff\ toner}$ versus pressure for DMA of 0.21, 0.47, 0.83, and 1.2mg/cm^2 when the conformable conductive foam layer was used as the receiving substrate. Figure 3 compares the results of using the conformable conductive foam as the receiving substrate to that of using the relatively stiff Ti-coated mylar. As the graphs show, for a fixed toner deposition, $D_{eff\ toner}$ drops rapidly in the low pressure region (P < 5 psi) as the applied pressure increases and then continues to decrease slowly in the higher pressure region up to the highest pressure applied. The general behavior of $D_{eff\ toner}$ vs. pressure is very similar for various DMA, with the conformable foam substrate, and with the Ti-coated mylar film.

Effect on the Fields

It is interesting to estimate the effect on the fields due to the range of toner dielectric thickness changes seen in the figures. The average pressure applied to a large extended solid area for a corotron transfer system is typically in the < 1 psi and the average pressure for biased transfer rolls is typically in the < 3 psi range. However, these average pressures can be magnified by more than 100 times for isolated high toner piles in a system due to the stiffness of the substrate. We will concentrate our discussion of the field variations with Deff toner on the low pressure regions. At low pressures the dielectric thickness introduced by the toner layer ranges between about 13 to 18 µm for the conformable foam when DMA going from 0.47 to 1.2 mg/cm^2. At similar low pressures and DMA changes, the dielectric thickness ranges between 14 to 21µm for the stiffer Ti-coated mylar substrate. The effect on the fields due to DMA changes turns out to be slightly higher in the case of the stiffer receiving plate. The stiffer mylar receiving plate is likely to simulate smooth paper or transparency.

As illustrated by equation 1, when the toner receiving substrate such as paper is at equipotential, the applied field above the toner layer is inversely proportional to the sum of the effective dielectric thickness of the paper, toner, and photoconductor. A typical dielectric thickness of a photoconductor is around 8 µm. The applied transfer field of high moisture paper will be found to be more sensitive to the toner dielectric thickness variations. For example, a typical dielectric thickness of a 20 lbs. paper ranges between ~ 25µm for a very low moisture condition and it is effectively zero for a high moisture condition.[1,2] With a high moisture paper at a low pressure, the applied transfer field, ET, will decrease by ~ 24% when the DMA is increased from ~ 0.47 mg/cm^2 to a higher value of ~ 1.2 mg/cm^2. With a low moisture 20 lbs. paper, the effect on the fields will be smaller, decreasing by only about 13% over the same DMA range.

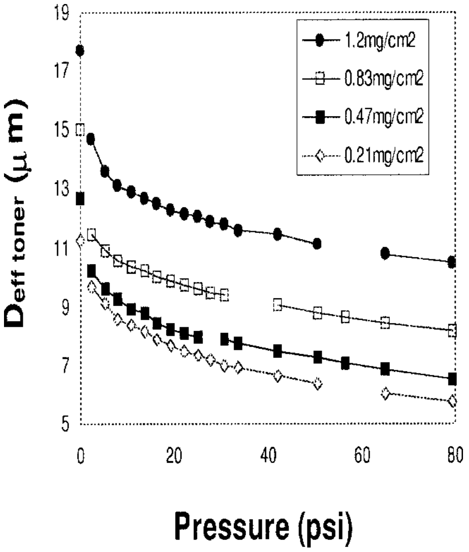

Figure 2. The effective dielectric thickness of the toner layers as a function of pressure using conductive conformable foam film as the toner receiving member.

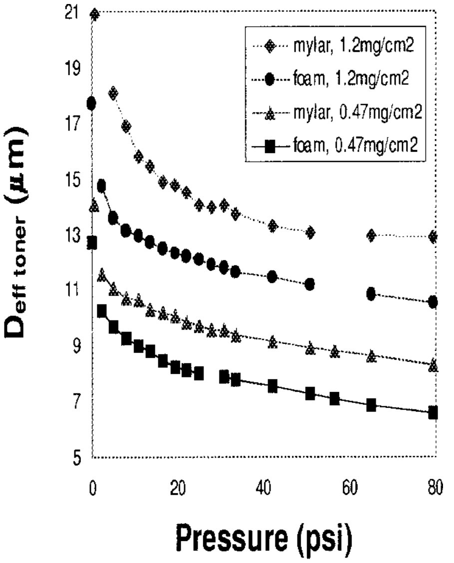

Figure 3. Comparison of $D_{eff\ toner}$ using conducting conformable foam film to that using mylar as the receiving substrate.

A well designed transfer system can often allow a transfer field change as much as 24% without major consequences. However, beside toner dielectric thickness, many other factors could also cause the transfer field to change, and a 24% change can have consequences relative to operating latitude for a transfer system. Also, larger ranges of DMA will obviously increase the latitude problem for a system. Finally, the effect on the fields due to DMA variations is expected to increase significantly for larger-sized toner particles.

Discussion of the Results Relative to Toner Packing.

The initial rapid decrease of $D_{eff\ toner}$ at pressures below ~5 psi observed in figures 2 and 3 is thought to be likely due to the rapid reduction of the macroscopic air gaps between the substrate and the toner piles caused by the relocation and compression of local high peaks of toner within the developed toner image topography. The further decrease of $D_{eff\ toner}$ at moderate and high pressures is thought to be explainable by the combined effects of the microscopic reduction of air gaps and the rearrangement or "squeeze" of the toner layers. The contact areas between toners or between toners and substrates are also expected to increase with pressure. The increase is not expected to cause rapid changes in the measured dielectric thickness, but it is expected to have significant consequences relative to toner cohesion and adhesion. The impacts on adhesion can be studied with our pressure cell, but discussion is beyond the scope of this paper.

To test whether the rearrangement and squeeze of toner have indeed happened, we used a NESA glass as a toner deposition plate and a mylar film as the toner receiving substrate. The NESA plate allowed the image of the toner to be captured with a CCD camera from the back of the glass while the mechanical pressure was applied. The position of the pressure cell was fixed so that the exact same area could be photographed at various pressures. The magnification of the camera was chosen such that individual toners could be identified and sized. The photographs show that the developed images contain the agglomerates of individual toners. Some of the toners from the top layers were pushed down to the bottom and some other toners were squeezed into denser low-height agglomerates as the pressure was increased.

The comparison in Figure 3 indicates a consistent ~ 2 μm higher effective toner dielectric thickness with the stiffer mylar than that with the conformable conductive foam at a fixed DMA over a wide range of pressures.

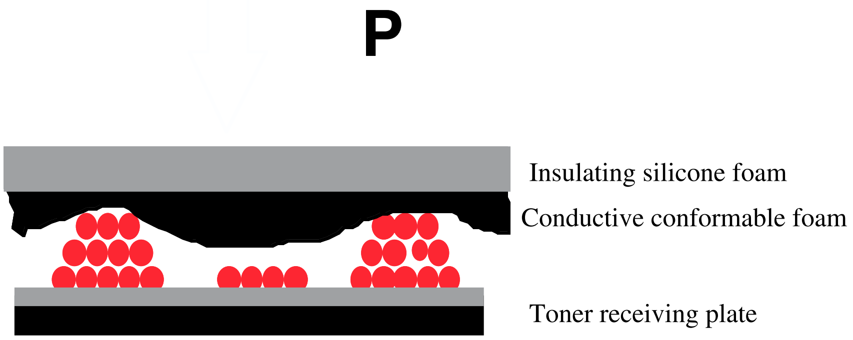

Figure 4. Demonstration of micro-conformability of conformable foam under pressure.

The smaller $D_{\text{eff toner}}$ with the conformable conductive foam could be explained by microscopic conformance of the foam. That is, the foam can be microscopically deformed according to the toner topography of the developed images as illustrated in Figure 4. The microconformance will reduce the air gaps during transfer and reduce the field limitations due to air breakdown. Obviously, transfer to a conformable material would be expected to have an advantage over transfer to a non-conformable member such as paper.

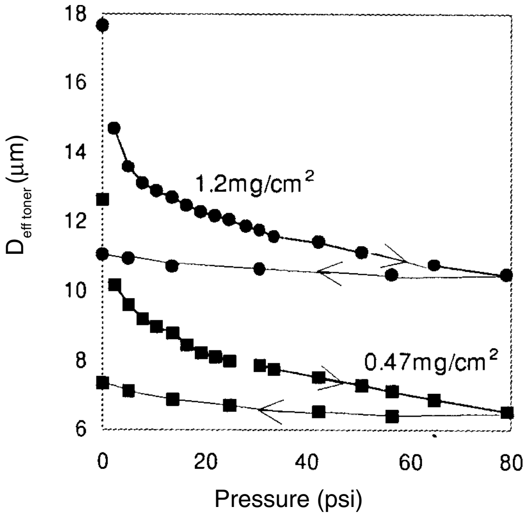

Figure 5. Hysteresis behavior of $D_{\text{eff toner}}$ versus pressure for toner deposition of 0.47mg/cm² and 1.2mg/cm² using conductive conformable foam as the toner receiving substrate.

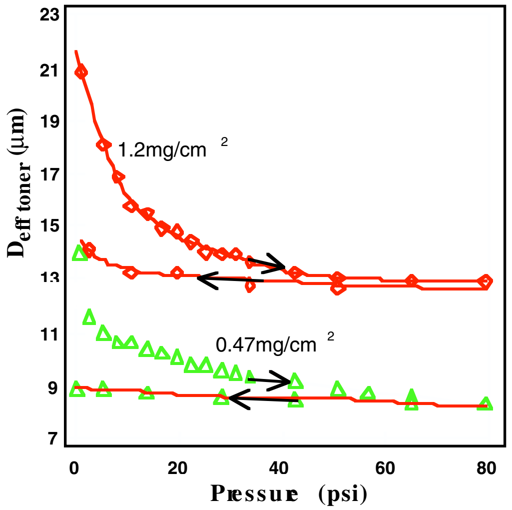

Figure 6. Hysteresis behavior of $D_{\text{eff toner}}$ versus pressure for toner deposition of 0.47mg/cm2 and 1.2mg/cm² using mylar as the toner receiving substrate.

Figures 5 and 6 show the hysteresis behaviors of $D_{\text{eff toner}}$ with toner deposition of 0.47mg/cm² and 1.2mg/cm² for the conformable conductive foam and mylar respectively. As the graphs indicate, Deff toner drops dramatically as the pressure is increased to 80 psi. It only increases slightly as the pressure is released, indicating that the reduction of air gap space and the rearrangement of toner are inelastic. This result suggests that mechanical pressure treatment should have a positive impact on the toner dielectric thickness, and on toner cohesion and adhesion even if it is applied prior to the transfer zone.

Summary

We have performed the measurements of the effective dielectric thickness of the toner layers under various pressures. Our results indicate that even with the relatively small (7µm) toner particle, the dependence of the effective toner dielectric thickness on DMA results in a significant decrease of the transfer field above the toner layer in high DMA regions compared to low DMA regions. The affect is expected to be enhanced with higher paper moisture conditions, larger toner particle sizes, and larger DMA variations.

Based on visual observations with a CCD camera, the large dependence of $D_{\text{eff toner}}$ on pressure is thought to be due to redistribution and squeeze of the toner piles, thereby reducing the air gaps between the toner receiving and the deposition substrates. As expected, a conformable receiving surface was found to have a lower $D_{\text{eff toner}}$ than for a stiff receiving plate. The trend of $D_{\text{eff toner}}$ is universal, but the specific shape of the curves is expected to depend somewhat on the development system and particularly on any development parameters that influence the developed image topography. Hysteresis measurements suggest that the redistribution of toner and the reduction of air gaps is mainly inelastic.

The measurements show that moderate average applied pressure of less than a few psi can significantly reduce $D_{\text{eff toner}}$, implying that even moderate applied pressures can effectively reduce the limitations to the transfer fields caused by air breakdown within the toner piles. We expect that the improved packing caused by pressures can have major impacts on cohesion and adhesion of the toner particles in the layer.

Acknowledgments

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