The Role of Dielectric Relaxation in Media for Electrophotography (II)
Imaging Electrostatic Non-uniformity in Paper

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(II) Imaging Electrostatic Non-uniformity in Paper

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Abstract

In a companion paper, we developed a mathematical model of electrostatic transfer in electrophotography. In that model, we applied the first principle treatment of charge transport to dielectric relaxation in receiving media such as paper during toner transfer. An important conclusion was that the traditional method of predicting the performance of a receiver by its resistivity, assuming an ohmic conduction model, is insufficient. Complete characterization of a receiver requires conditions closely simulating the charge supply and charge transport that occur in the actual electrophotographic process. In this paper, we show that the open circuit measurements of the electrostatic charge decay (ECD) technique provide the necessary conditions for complete characterization. Using the ECD technique with a computerized scanner, we demonstrate that electrostatic non-uniformity in paper can conveniently be mapped. Furthermore, several important print quality metrics, including optical density (which relates to transfer efficiency) and image noise (which relates to uniformity of transfer), can be correlated with ECD voltage and a "characteristic length" (the typical scale of voltage variations) in the electrostatic map.

Introduction

A typical transfer subsystem in electrophotography (as shown in Figure 1) consists of a photoreceptor (PR), the toner layer, an air gap, the receiver (such as a sheet of paper or a transfer belt), and a bias voltage, V_b, supplied by a corona source or a power supply connected to a transfer roller. In the transfer process, the driving force is the electric field, $E_t(x)$, in the toner layer, which is determined by the applied bias voltage and the voltage drop across the individual layers in the model. To maximize the voltage (and hence the field) in the toner layer, the voltage drop across the receiver layer must be minimized, and this can be achieved by controlling dielectric relaxation in the receiver material.

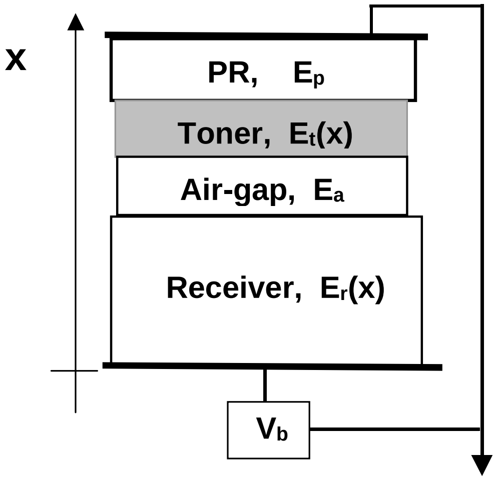

Figure 1: Physics of transfer: One-dimensional schematic of transfer nip

Dielectric relaxation in paper is now usually characterized by its ohmic resistivity. ASTM standards exist for measuring volume and surface resistivities (ASTM D4949-89).[1] While the methods prescribed are intended as quality control tools in papermaking, it is widely acknowledged that measurements obtained by these methods are not good predictors of paper performance in electrophotography. Resistivity (or conductivity) measurement is not a reliable means for predicting, for example, transfer efficiency or print quality. The traditional resistivity measurement method rests on the underlying assumption of an ohmic model of conduction in paper. Unfortunately most commonly-used papers (and other semi-insulating materials) are non-ohmic, as is evident in the voltage decay data shown in Figure 2.

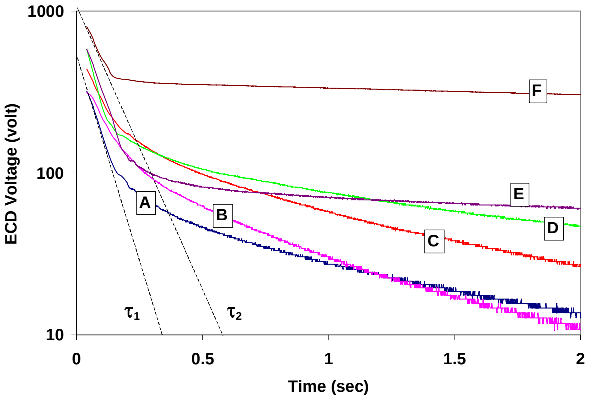

Figure 2: Non-ohmic dielectric relaxation in papers

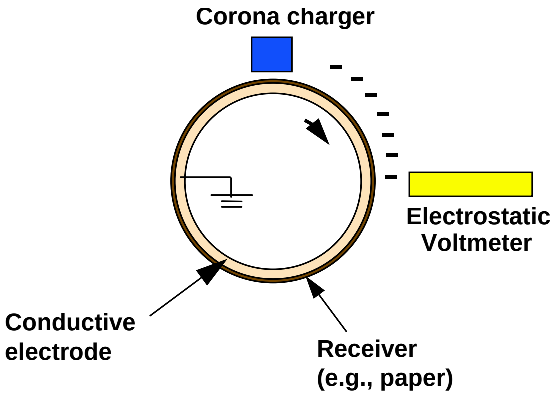

Figure 3:. Schematic diagram of ECD measurement of paper

In Figure 2, the voltage decay of various paper samples is plotted logarithmically versus time. If the voltage decay process were ohmic, we would expect the voltage decay to follow the dotted lines with time constants τ_1 and τ_2. In reality, all of the decay curves shown deviate from linearity in the semi-log plots. The physics behind this non-ohmic behavior is discussed in detail in a companion paper[2]. In essence, dielectric relaxation in paper involves not only the paper's intrinsic conductivity, which is the product of the intrinsic charge density and mobility, but also its charge lifetime and the injection of charge at the interface. Charge mobility in semi-insulators is typically low (on the order of 10^{-6} cm^2/V-sec) and is often complicated by its field dependence. Charge trapping sometimes occurs in the bulk of the receiver. Charge injection is also likely to be field dependent. Thus, a number of fundamental phenomena contribute to the complex dielectric relaxation behavior of paper. Given this new understanding, we conclude that to predict paper performance in the toner transfer process a new approach to characterization is needed. In this paper, a novel method called the Electrostatic Charge Decay (ECD) technique is introduced.[3-7] This method provides an "open-circuit" measurement of the dielectric relaxation behavior of paper (Figure 3). The method not only simulates the charge supply and charge transport of the actual printing application, but also provides the basis for a computerized scanner method that can be used to "image" the non-uniformity inherent in a sheet of paper.

ECD Characterization of Paper

The two measurement modes made possible by our implementation of the ECD method are: 1) "static" measurement of the voltage decay at a given location on the paper (as illustrated in Figure 2), and 2) mapping of the overall non-uniformity of the paper. Both methods use a computer-controlled scanner. In both modes, a conductive drum or plate is used as a ground reference surface and also typically serves as an electrode.

During a "static" scan, a corona charger deposits a charge onto the paper. An electrostatic probe then moves to the location of interest, scanner motion stops, and the probe monitors voltage decay as a function of time at that location. Typical voltage decay data are shown in Figure 2 above. In this figure, samples A, B and C are off-the-shelf "brand-name" 24 lb uncoated laser printing papers with very similar smoothness. Sample D is a "high-quality, ultra-smooth" 28 lb uncoated laser printing paper. Samples E and F are relatively heavy weight coated papers. It is very clear from this data that the voltage decay in all these samples is non-ohmic and that the relaxation characteristics differ widely from sample to sample. The methodology for extracting relevant relaxation parameters from such voltage decay data is discussed in detail in our companion paper.[2] In the present study, for the sake of simplicity we determined the voltage at 0.1 sec as a representative measure of the relaxation characteristic of each paper sample. The observation time is based on the process time of the printer used in this study for print testing. The printer has a rated print speed of 24 ppm. With an observation time less than or equal to the process time, we can be sure that the voltage measured is relevant to the process speed. The numerical data from this set of samples is used below to develop a correlation between the ECD voltage and print quality.

The other measurement feature of our ECD paper characterization system is mapping mode. Mapping mode, in which the overall surface of the sample is scanned under computer control, with corona charging applied and non-contact voltage measurements taken, results in a two dimensional representation of the voltage distribution across the sample. Typically, a false-color scale is used to show the variations in voltage. In Figure 4, we show binarized versions (for clarity in monochrome reproduction) of this type of map. From these maps, the statistics of the voltage distribution (such as mean, standard deviation, and range) can readily be obtained. Furthermore, we can estimate one or more "characteristic lengths" that typify the length scale of voltage variations in the map, as illustrated by the voltage scans in Figure 5.

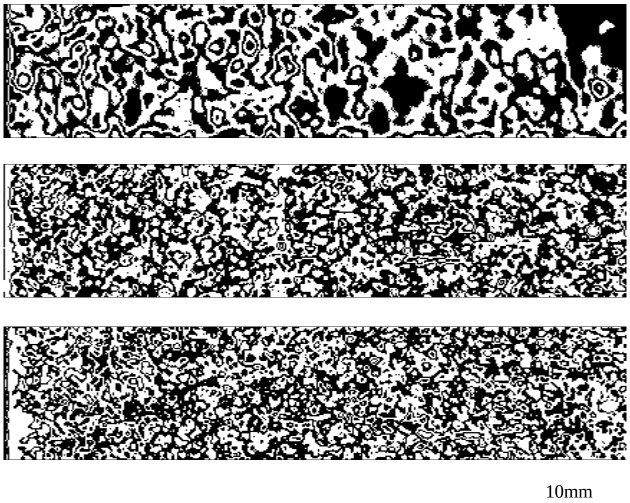

Figure 4: Binarized ECD mapping of dielectric relaxation in paper

Print Testing and Correlating ECD Measurements with Print Quality

In this study, a monochrome laser printer (Hewlett Packard Laserjet 5Si, 24 ppm) was used for the print testing. A very simple test target (shown in Figure 6) was designed, with half of the page covered by 70% gray and the other half left white (non-printed). During printing, the gray area was at the leading edge. After the test, several print quality metrics were measured using an automated image analysis system (QEA IAS-1000).[8] The measurements made included: optical density and mottle in the gray area and background in the white area. For each sample, enough measurements were made to ensure the statistical significance of the assessments.

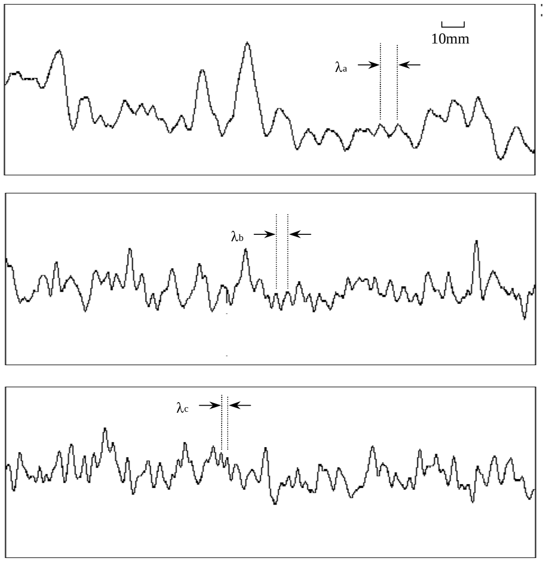

Figure 5: Voltage scans demonstrating the concept of a one-dimensional "characteristic length"

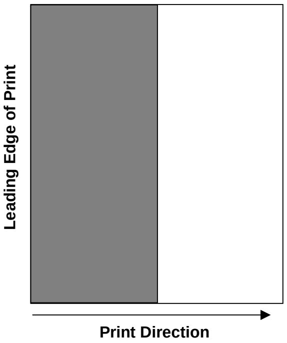

Figure 6: Test target

In Figure 7, the optical density measured in the 70% gray region is correlated with the mean ECD voltage obtained in the uniformity maps. As shown, the correlation is good and suggests that the mean ECD voltage can be used as a reliable indicator of transfer efficiency. High mean ECD voltage means slow dielectric relaxation in the receiving media in the transfer nip. Consequently, the electric field in the toner layer (see Figure 1), the driving force for transfer, is reduced. The transfer efficiency is thereby reduced, lowering optical density on the print.

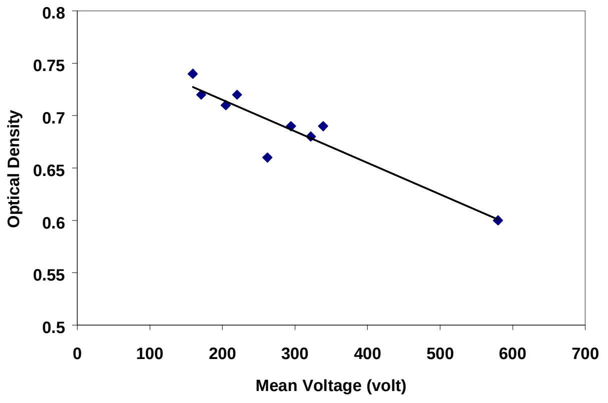

Figure 7: Optical density versus mean voltage in ECD map.

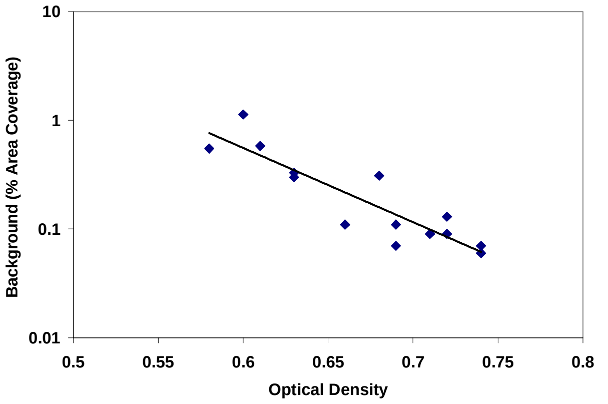

Figure 8: Background in non-print area versus optical density in 70% gray printed area.

When the transfer efficiency is low, toner residue is left on the photoreceptor. In our print tests, we found that this toner residue created background (unintentional toner deposits) in the white areas of the test prints, and the background level increased with the ECD voltage of the test sample. The background level was measured using the QEA IAS-1000 system and is quantified by the percent toner coverage. In Figure 8, a negative correlation between background in the white area and optical density in the gray area is shown. Combining these results with those in Figure 7, a consistent picture emerges: as the ECD voltage increases, transfer efficiency decreases, optical density decreases and background increases.

Another important print quality metric is image noise. We measured image noise in the print samples using the IAS-1000 system, and applied the mottle metric defined in the ISO-13660 International Print Quality Standard.[9,10] Mottle is a measure of the variation in print density within a test sample, i.e., it is a measure of the uniformity of optical density. In addition to variation within a sample, optical density may also vary from sample to sample. Our experience shows that these inter-sample density variations can make interpretation of mottle measurements rather difficult. To overcome similar difficulties, we had previously developed a technique in which we normalized the mottle value by the percent reflectance of a sample, a technique we applied successfully in quantifying ink coalescence on media in inkjet printing.[11] Using the same technique, we found a very interesting and illuminating correlation between the mottle/reflectance ratio on the print samples and the characteristic length estimated from the corresponding ECD uniformity maps. The results are summarized in Figure 9 and suggest that the spatial variation in dielectric relaxation characteristics affects uniformity of toner transfer and hence print density. An estimation of the characteristic length in an ECD uniformity map thus provides a tool for predicting and even improving print uniformity.

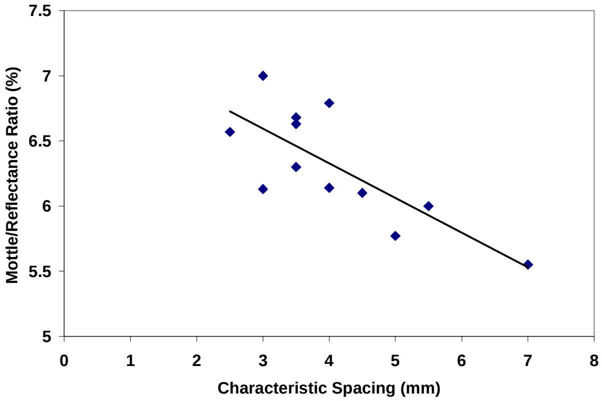

Figure 9: Mottle to reflectance ratio in print target versus characteristic spacing in ECD map of paper.

Discussion

Being able to predict print quality from the electrical properties of paper has been a long standing problem. While the traditional method of measuring resistivity has some value as a quality control tool in papermaking, the usefulness of resistivity in predicting transfer efficiency and print quality is widely seen to be very limited.

The Electrostatic Charge Decay (ECD) technique is an alternative to the traditional approach. The ECD technique closely simulates the actual charge supply and charge transport in a typical transfer subsystem in an EP printer. The technique therefore provides a much better correlation between the measurements and print performance, as the results presented here illustrate. Furthermore, because ECD is a non-contact method, it lends itself to computer-controlled scanning. This represents a significant improvement over the traditional contact methods, which are limited to single-location measurements.

What contributes to electrostatic non-uniformity in paper? The conventional wisdom says that paper formation (the spatial variation in mass density) is the dominant factor. Based on our research, it is now clear that formation plays a much less significant role than previously assumed. As suggested in our companion paper on the role of dielectric relaxation in toner transfer, transfer efficiency depends on a host of factors including intrinsic charge density, field-dependent mobility, charge trapping and lifetime, and charge injection at the interfaces. This being the case, the chemical makeup of the paper and its spatial distribution is at least as important as the mass distribution of its fibers. Charge injection at the interfaces, which is a factor much neglected in the past, is now surfacing as one of the most critical contributors to electrostatic non-uniformity. For example, if the paper is in contact with an electrode, the contact mechanics (which include factors such as the surface roughness, paper compliance and contact pressure) determine the nature of the contact and the efficiency of charge injection. Injected charge from the electrode is a very important source of charge supply for the dielectric relaxation process in semi-insulating materials such as paper.

Although some of the factors discussed above may have been considered by others, the theoretical model discussed in our companion paper and the ECD technique for paper analysis presented here provide a clear and consistent methodology for characterizing the dielectric relaxation properties of paper.

Conclusions

We have introduced a novel measurement technique for characterizing the dielectric relaxation characteristics of paper. The method yields measurements that are relevant to the toner transfer process. For the first time, ECD mapping provides electrostatic images of the non-uniformity of paper. The mean electrostatic image correlates with the resultant optical density and the background level in the print. The spatial variation in ECD voltages, quantified by a "characteristic length," correlates with the image noise resulting from uneven toner transfer. The measurement tool, together with the theoretical model presented in our companion paper, gives powerful new insight into the underlying physics of the transfer process and provides a consistent methodology for characterization and improvement of paper for electrophotography.

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Biography

Dr. Ming-Kai Tse founded QEA, Inc. in 1987. The company designs and manufactures automated quality control test systems for manufacturing and R&D applications in digital printing. Dr. Tse was a professor of Mechanical Engineering at the Massachusetts Institute of Technology between 1982 and 1989. At MIT he specialized in the areas of manufacturing, non-destructive testing, and quality engineering. Dr. Tse received his BS degree in Mechanical Engineering from Cornell University and his MS and PhD degrees, both in Mechanical Engineering, from MIT. Contact at mkt@qea.com.