Performance Evaluation of Rollers for Charging, Development and Transfer in Electrophotography

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Abstract

The performance of rollers for charging, development, and transfer processes in electrophotography depends critically on dielectric relaxation of the semi-insulating dielectric layers in these devices. In these layers, the progress of dielectric relaxation is controlled by the charge injection from bias and the charge mobility, rather than by the bulk resistance. Based on the physical principle of the processes, the shortcomings of the traditional roller characterizations by resistance measurements are explained, and a novel characterization technique that simulates more closely the actual processes is introduced. This "Electrostatic Charge-Decay" (ECD) technique is based on open-circuit measurements of dielectric relaxation, and capable of examining the transient states and spatial variations efficiently and non-destructively.

Introduction

Charging, development, and transfer rollers are critical for proper functions and good performance of electrophotographic (EP) printers. The rollers consist of a conductive shaft overcoated with a more resistive, semi-insulating dielectric layer about 100 µm thick. The key mechanisms in EP processes involving these rollers can be described qualitatively as follows.

In roller charging of photoreceptors (PR's), the PR's are charged with ions created by electrical breakdown in the air-gap between the roller and the PR.[1] As the ions from air breakdown deposit on the PR, the counter ions accumulate on the roller surface. This reduces the voltage across the air-gap, and prematurely terminates the air breakdown and the charging of PR. To achieve sufficient charging, the counter-ions on the roller surface must be efficiently neutralized with charges injected from the bias connected to the roller shaft. This reduces the voltage across the overcoat layer and keeps the voltage across the air-gap high enough for continued air breakdown.

In single-component development (SCD), depicted in Fig. 1, toners are predominantly charged as they pass through the metering blade (MB), receiving (e.g., negative) charges from the bias V_{B1}.[2] At this time, (positive) counter-charges are injected into the dielectric coating layer of the donor roll from the bias V_{B1}. This enhances the amount of charge that toners can acquire from the MB, and increases the adhesion of toners to the roller. At the deposition step, as toners move toward the PR, the counter-charges would impede this toner motion unless they are neutralized with (negative) charges introduced into the layer from bias V_{B2}. These injections of charges into the dielectric overcoat layer are associated with reduction of the voltage across the layer.

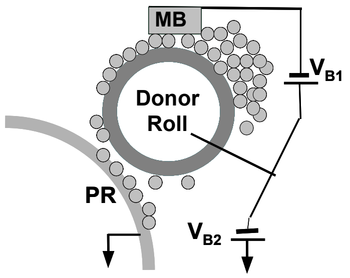


Fig.1.Development roller in single-component development

In electrostatic transfer of toners from PR or intermediate transfer belt to output media (paper),[3] a bias voltage is applied across the multi-layer consisting of the toner-donor, the receiver, the toner layers, and air-gap. A successful transfer requires distributing a large fraction of the bias voltage to the toner layer. This is made possible by reducing the voltage across the donor and the receiver layers, i.e., the layers with large thickness.

The conventional method for evaluating these rollers is by resistance measurement. However, the results from this method have been poor in reproducibility and/or inconsistent with device performance. In this paper, we first explain the shortcomings of the resistance measurements. This is followed by the description of a novel characterization technique, "Electrostatic Charge Decay (ECD)",[4] including its relations to the EP sub-processes, described above, and the physics of dielectric relaxation (DR) in semi-insulators (SI).

The resistance R is given by the conductivity σ and the layer thickness L as $R = L/\sigma$. The conductivity $\sigma = \mu q_i$ is the product of charge mobility µ and intrinsic charge density q_i. Thus, R and σ are the bulk properties of the layer, independent of the condition of the interfaces with the electrodes at the surface or the shaft. Furthermore, the resistance determines the current only if the electrodes form "Ohmic contacts", which supply charges just sufficient to maintain the intrinsic value q_i. However, this is not always the case for rollers in EP applications. With "non-Ohmic" contacts, more or less charges can be injected into the sample, causing the charge density $q(x, t)$ and the field $E(x, t)$ to be functions of time t and position x in the sample. In general, the injection current depends on the amount of free charges available and the field strengths $E(0, t)$ or $E(L, t)$ at the contacts, $x = 0$ or L. It can also be affected by the physical conditions (e.g. pressure, adhesion, smoothness) at the interface. In such cases, the (bulk) conductivity σ, or resistance R has little use as a figure of merit for the electrical characterization of the device.

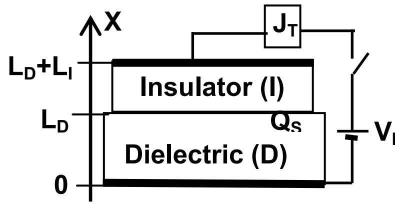


Fig.2. Series-capacitor configuration of rollers in EP

From the above descriptions, it is clear that the essence of roller operations in EP share a common configuration shown in Fig. 2. It consists of a layer of semi-insulating dielectric (D) on the conductive substrate and an insulator layer (I) (photoreceptor-in-dark, toner-layer, and/or air-gap), connected in series to a constant bias voltage V_B. At the entrance to the roller nip, (at t = 0), the voltages across each of the two layers V_D and V_I, are divided in inverse proportion to their capacitances, $C_D = \varepsilon_D/L_D$ and $C_I = \varepsilon_I/L_I$. Here, ε and L denote the permittivity and thickness, respectively, of the layers. But due to the semi-insulating nature of the dielectric layer, the voltage V_D decreases with time, while the voltage V_I increases. This "dielectric relaxation" of the D layer promotes the progress of the EP processes, as described above qualitatively.

An important difference between the resistance measurement and the dielectric relaxation of rollers in EP processes (and the series-capacitors in Fig.2) is that in the latter cases, a constant (bias) voltage is applied across both the semi-insulator (D) and the insulator (I) layer. Therefore, the voltage across the semi-insulator is not constant in time (as in resistance measurements). The relaxation actually occurs under a decreasing voltage, i.e., under an open-circuit condition.

Charge Transport Model of Dielectric Relaxation

In some previous works on analyses of EP processes,[5] the time dependence of the process was associated only with the rotation of the rollers. The charge transport in the semi-insulating layer has a speed $\mu E \approx 1$ cm/sec (with mobility $\mu \approx 10^{-5}$ cm^2/Vsec and field $E \approx 10^5$ V/cm). This is much slower than the mechanical motion of the rollers ($\approx$ 25 cm/sec at 60 cycles/min). Thus, the charge transport causes a larger constraint on the time dependence of the EP process, and has to be considered explicitly. Furthermore, using the above typical values of μ and E, the transit time required for a charge to move across a layer of thickness $L \approx 100$ μm is $t_T = L/\mu E \approx 10^{-2}$ sec, or longer. This is the same order of magnitude or longer than the conventional "dielectric relaxation time", $t_R = \varepsilon/\sigma \approx 10^{-3}$ sec (with $\varepsilon \approx 10^{-13}$ F/cm and $\sigma \approx 10^{-10}$ S/cm). Under this condition ($t_T > \approx t_R$), the influence on the motion of a charge from other charges (space-charge effects) cannot be ignored.

In this work, the dielectric relaxation of rollers in EP processes or in the model system of series capacitors (Fig.2), with non-Ohmic contacts is analyzed with the first principle charge transport equations. The motion of charges in the dielectric layer is determined by the continuity equation for the positive (and negative) charge densities q_p (and q_n), (omitting the subscripts p and n),

$$\partial q(x, t)/\partial t = -\partial J/\partial x = -(\partial/\partial x)(\mu q E)$$

where $J(x,t) = \mu q E$ is the conduction current density in the D layer. The boundary condition at the substrate interface, x = 0, is given by the current injected into the dielectric layer. This injection current density can be expected to increase with the field E(0) at the contact. For lack of better knowledge, it is assumed to be linear in E(0), with a proportionality constant s specifying the injection strength, i.e., $J(0,t) = sE(0,t)$. There is no charge injection into the I layer.

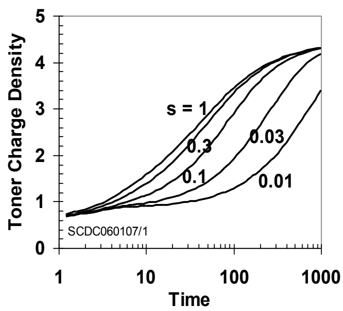


Fig.3. Growth of toner charge in SCD with time, for varying injection strength s, from Charge-Transport model.

The performance parameters of EP sub-processes involving a roller are analyzed (simulated) with the mathematical procedure described above. In SCD (Fig.1), the analysis is first applied to the nip at the metering blade to examine the time dependence of toner charging.[2] Figure 3 shows the dependence on time and injection strength of the growth of toner charge. The similar analysis of toner deposition at the roller-PR nip is shown in Fig. 4 by the increase of deposition efficiency with time and injection strength. The deposition efficiency is defined as the fraction of toner-layer thickness where the field is in the direction of moving toners toward the PR.

A common feature in these figures is that the performance parameters, i.e., charge density in Fig.3, and deposition efficiency in Fig.4, both approach their respective asymptotic values after a long process time (> $1000t_o$), independent of the charge injection strength s. However, the time required to reach this asymptotic value increases approximately in inverse proportion to the injection strength s. Consequently, the performance parameters show a strong dependence on s in the time range of a few tens to a few hundred time units.

A similar plot of the decays in the voltage across the D-layers of series-capacitors (Fig.2) is shown in Fig. 5. Much resemblance in the dependence on injection strength and time can be seen between Fig. 5 and Figs. 3 or 4. This is a strong indication that the progress of these EP processes is closely related to the dielectric relaxation of the semi-insulating dielectric layer under an open-circuit condition as in the series-capacitor configuration.

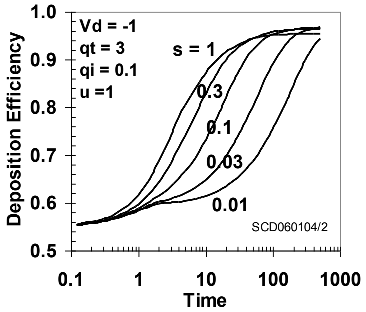


Fig.4.Growth of toner deposition efficiency in SCD, for varying injection strength s, from Charge-Transport model.

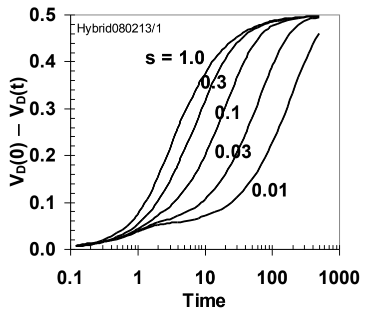


Fig.5. Voltage decay in dielectric layer of series-capacitors, injection strength s varied, from Charge-Transport model.

Similar analyses applied to roller-charging and transfer processes lead to the same conclusions.[1, 3] The dielectric layer is generally made of heterogeneous composite polymers. The spatial uniformity of electronic properties unlikely reaches the microscopic (pixel-size) scale. The results shown in Figs. 3 to 5 indicate that to avoid manifestation of spatial variations in injection strength s within a given roller, or from roller-to-roller, the time allotted for the relaxation in each process should be more than several hundred time units.

In these analyses, the unit of time is the nominal transit time, defined by the layer thickness L, charge mobility μ, and bias voltage V_B as, $t_T = L^2/\mu V_B$. With the typical values in EP applications, the time unit has a value of $t_T \approx 5$ msec. The results in Figs. 3 to 5 indicate that it requires a "relaxation time" t_R greater than a few hundred times t_T (≈ 1 sec) for the process to become nearly independent of charge injection strength for s > ≈ 0.01. Thus, in order to avoid the consequence of the spatial and/or roller-to-roller variations of injection strengths, the "process time" t_P allotted for the charging, deposition, or transfer should be longer than the "relaxation time", on the order of one second.

The time allotted for each process t_P can be estimated from the print speed (ppm) and the nip width (w_{nip} in mm) as t_p(msec) =240(wnip/ppm). For typical nip widths of 1 to 10 mm, and the print speed desired today (> 60 ppm), the process time available is less than about 40 msec, which is an order of magnitude shorter than the relaxation time estimated above (≈ 1 sec). It follows that in high speed EP, the charging, deposition or transfer processes may not have sufficient time for the rollers to reach the fully relaxed state, unless the charge injection strength is uniformly large enough (s > ≈ 1 unit). In other words, the performance is very likely determined by the transient state of the device, and not by the fully relaxed state.

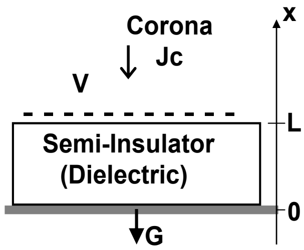


Fig.6. Schematic of roller characterization by ECD technique

Electrostatic Charge Decay Technique

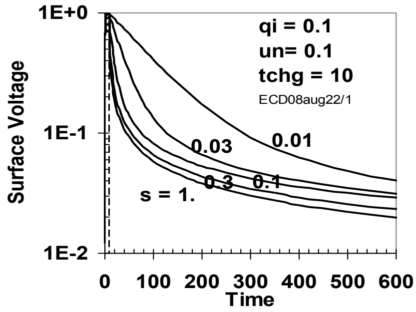
To simulate the open-circuit dielectric relaxation, (and to circumvent the shortcomings of closed-circuit resistance measurements), we introduced a technique called "Electrostatic Charge Decay" or ECD.[4] As shown schematically in Fig. 6, the roller sample on a grounded substrate is charged with a corona current J_C at the semi-insulator surface. The decrease of J_C with charging time is monitored. In addition, the surface voltage is measured with a non-contact electrostatic probe. The surface voltages rise during corona charging, and decay after the charging is over. By scanning the corona source and voltage probe above the sample surface, this technique provides additional advantages of non-contact, non-destructive and efficient mapping of a large area of the sample for evaluating the uniformity of the device. This ECD experiment can also be modeled with the charge transport equations described above, with minor changes in the boundary conditions. The corona current J_C is related to the surface voltage V(t) by,

$$J_C(t) = J_{mx}[1 - V(t)/V_{mx}]$$

where J_{mx} and V_{mx} are two empirical parameters for the corona device, representing the initial current (at V = 0), and the saturation voltage (at $J_C = 0$), respectively.

Figure 7 shows the rise (t ≤ 10) and decay (t > 10) of surface voltage after corona charging for a short time t = 10, calculated for different values of injection strength s. The decaying voltages reflect the size of injection strength (slower for smaller s). A set of the corresponding experimental data is also shown.

The current mode of ECD data are shown in Fig. 8. The current decreases to a steady-state value (from J_{mx} at t = 0). The steady-state currents are higher for higher values of s. A set of corresponding experimental data are also shown for comparison.



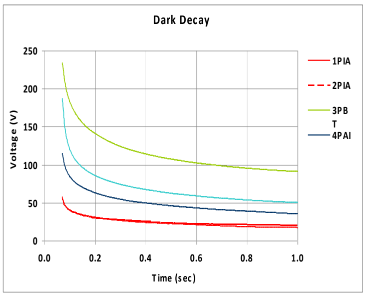
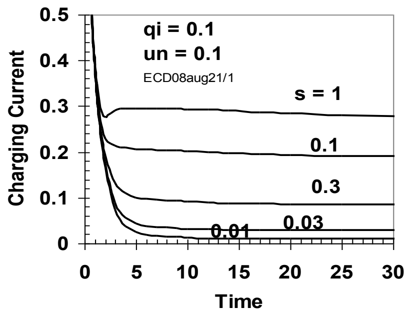


Fig.7. Calculated ECD surface voltage, charged to t = 10, then decay, with various injection strength s (upper figure); Corresponding experimental data (lower figure)



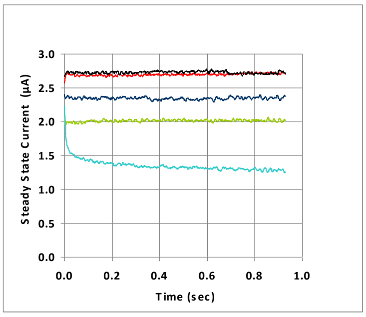


Fig. 8. Current mode of ECD data, calculated (upper) and experimental data (lower)

Examples of scanning and mapping the full surface of a charging roller are shown in Fig. 9. The full-surface ECD data clearly demonstrate the correlation between ECD voltage (V_{ECD}) and the print quality. The non-uniformity in V_{ECD} can be mapped directly to a print density variation map and a background map. Such results clearly demonstrate the efficacy of the ECD technique.

Conclusions

An ideal electrical characterization of rollers for EP application should detect the microscopic (pixel-size) spatial variation in dielectric relaxation, manifested within time limits of high speed printing applications. It is not sufficient to observe the fully relaxed state which can only be reached in a time much longer than the practical process time. Since the dielectric relaxation is induced mainly by charge injection under the decreasing field, the characterization technique should simulate the same condition with open-circuit measurements.

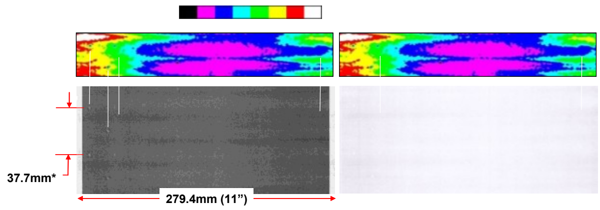


Figure 9. ECD data of Charge Rollers. Prints and background noises are shown to reproduce in ECD voltage maps.

The Electrostatic Charge Decay (ECD) technique simulates more closely the actual EP processes than the closed-circuit resistance measurements. Furthermore, the technique is capable of non-destructive monitoring of the transient spatial fluctuation, examining the ambi-polarity of charge transport required in SCD development rollers and intermediate transfer belts for color images. The technique has been successfully used by many device suppliers and printer manufacturers.

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Author Biography

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