Gray Level and DMA Estimation in Monocomponent Development Systems

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Abstract

In our companion paper, we introduced a novel field calculation technique for obtaining the electric field in the developer gap. In this paper, we demonstrate how normal and horizontal fields obtained from this method can be used to estimate gray level and developed mass per unit area (DMA) of a given pattern. The estimation procedure is phenomenological, but it exploits the physics governing toner movement in the development nip to account for observed feature size dependence of toner development. Estimated DMA specifies developed mass at each point in the calculation grid (3 µm cell). Thus, for any input bitmap, DMA at the subpixel level can be accurately predicted over the entire image. Using two different print engines and various bitmaps, we present simulation results and measurements, which are in good agreement. DMA measurements are collected from measured average toner mass data and scanned images using video microscopy. We calibrated microscopic grayscale data to the toner mass measurements, so that DMA can be obtained directly from scanned gray values.

Gray Level and DMA Measurements

A 1200 dpi printer and a 600 dpi printer were used in our experiments. The printers' fusers were disabled to prevent developed toner from melting into the paper. A 1cm × 1cm image consisting of one constant gray level was converted into a halftoned bitmap. The halftoned binary bitmap no longer consists of one gray level, and its darkness can only be expressed in terms of %-coverage, which is the ratio of the area occupied by the black pixels to the total image area. Note that gray level-% and %-coverage are equivalent measures (the former represents the darkness of a grayscale image and the latter the darkness of a halftoned bitmap). The converted bitmap was printed and then scanned using a video microscope system. The digitized image contains 480×640 pixels, each of which has a gray value ranging from 0 to 255. Calibration curve data was obtained by measuring the amount of developed toner mass using an analytical balance. This process was repeated for various gray levels from 23% to 100%-coverage and different feature sizes (0.3cm × 0.3cm and 0.5cm × 0.5cm). A 7th order polynomial fit was performed on the average gray level and DMA data, from which calibration curves were obtained. These calibration curves allow both forward (from gray level to DMA) and backward (DMA to gray level) calibration. Forward calibration is used to obtain DMA directly from scanned grayscale images and backward calibration is used to generate grayscale images from predicted DMA. The forward calibration curve for the 600 dpi printer is shown in Figure 1.

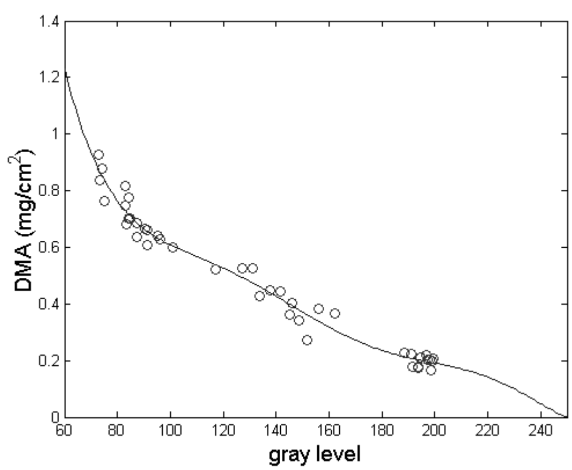

Figure 1. Forward calibration curve for the 600 dpi printer

Feature Size Dependence of DMA

We have observed that the development width of a simple pattern such as squares and lines depends on the feature size. For example, the developed width of a 40 pixel × 40 pixel square is slightly smaller than 40 pixels whereas a single pixel wide line develops more than the original feature size, as illustrated in Figure 2. Our findings lead us to conclude that this anomaly is due to the horizontal fields and AC bias applied to the developer sleeve. The AC bias causes toner particles to bounce back and forth in the nip region,[1] while the horizontal field draws the toner towards the middle of the pattern.[2] The combined effect is that large features are affected by the horizontal fields more than smaller patterns since the normal field of large patterns becomes neutralized more slowly than that of small features[3] and hence large patterns finish developing later than smaller ones, allowing more horizontal displacement.

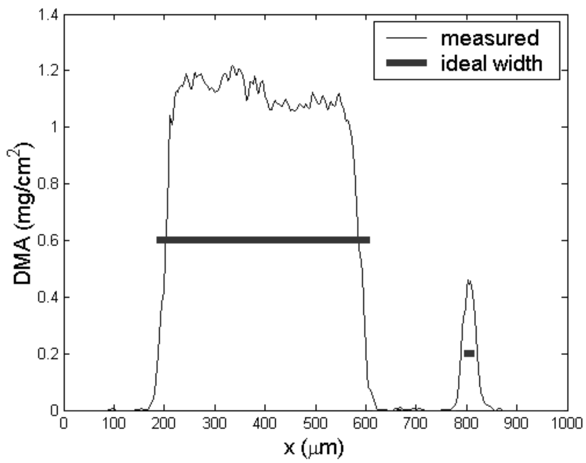

Figure 2. Measured development vs. ideal width

Gray Level and DMA Estimation

Our DMA estimation technique first scales the work done on toner particles (see Figure 3) by the electric and other forces in the gap based on measured developed toner mass data to obtain *base* DMA. The horizontal fields are then utilized to determine horizontal toner displacement. Figure 4 shows a cross section along the *x*-axis of the base DMA and measured DMA using the bitmap in Figure 5 (1200 dpi). As the line width increases, the base DMA increasingly overpredicts the development width when compared with the measured DMA. This is subsequently corrected for the effect of horizontal field.

Base DMA

The total forces acting on toner particles in the gap are quite complicated. In addition to the development field a first principles treatment would need to account for magnetic forces acting on toner particles arising from the magnetic brush, particle collisions and mutual repulstion, windage factors, particle-to-particle adhesion and perhaps other forces as well. Calculations attempting to account for even some of these factors quickly become quite involved.[4] We instead adopt a phenomenological approach based on uniform toner distribution (Figure 3) in the gap and approximation of the non-electric forces using a phenomenological "work function."

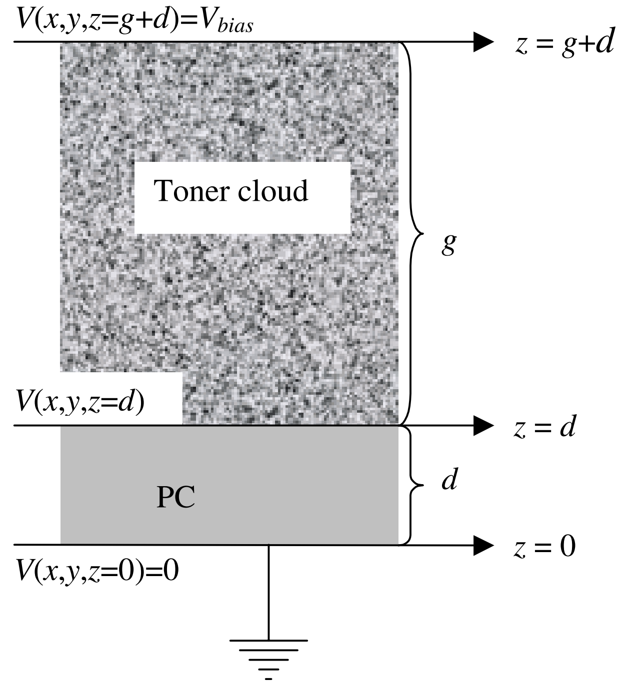

Figure 3. PC and developer

The total work done (in the z direction) by the electric and other forces in the developer gap where a uniformly distributed toner cloud is formed (Figure 3) is given by

$$W_{total}(x,y) = W_{elec}(x,y) + W_{other}(x,y) = \int_d^{g+d} F_{elec}(x,y,z)dz + \int_d^{g+d} F_{other}(x,y,z)dz. \quad (1)$$

The toner used in our test print engines is insulative. Thus, the work done by the electric force is linearly proportional to the normal electric field and we assume without any loss of generality that F_{other} is independent of x and y (e.g., the magnetic force in the gap varies little in the horizontal directions when a large parallel-plate configuration is concerned). Then

$$W_{total}(x,y) = q_t\left(\int_d^{g+d} E_z(x,y,z)dz + \frac{W_{other}}{q_t}\right), \quad (2)$$

where q_t is the toner charge and E_z is the normal electric field, as similarly derived by Yi et al.[3] Our conjecture is that base DMA is directly proportional to Eq. (2)

$$DMA_{base}(x,y) = k_0\left(V(x,y,d) - V_{bias} + V_0\right). \quad (3)$$

$V(x, y, d)$ is the potential at the PC surface and V_{bias} is the bias voltage supplied to the developer (Figure 3). k_0 is calibrated to measured developed toner mass data via

$$k_0 = \frac{DMA_{\max}}{V_{solid} - V_{bias} + V_0}, \quad (4)$$

where V_{solid} is the large area potential at the PC surface and DMA_{max} is obtained from measured DMA data. The phenomenological factor $V_0 = W_{other}/q_t$ is adjusted for different print engines using the calibration pattern in Fig. 5.

Horizontal Displacement of Toner

Consider a single toner particle at rest located at (x, y, z), as illustrated in Figure 6. Since

$$q_t E_z(x, y, z) = m_t \ddot{z}(t), \quad (5)$$

the time required for its infinitesimal vertical movement Δz due to the normal field E_z is

$$\Delta t = \sqrt{-\frac{2m_t \Delta z}{q_t E_z(x, y, z)}}, \quad (6)$$

where m_t and q_t are the mass and charge of the particle, respectively. During Δt, the particle's displacement in the x-direction is

$$\Delta x = \frac{q_t E_x(x, y, z)(\Delta t)^2}{2m_t}. \quad (7)$$

Calculating the horizontal displacement iteratively with a reasonably small Δz while accounting for interactions among toner particles is computationally very expensive. Our approach is to estimate the final displacement with

$$\Delta x_{final} = \eta_x \frac{q_t E_x(x, y, z_0)(\Delta t_{final})^2}{2m_t}, \qquad \Delta t_{final} = \sqrt{\frac{2m_t g}{q_t E_z(x, y, z_0)}} \quad (8)$$

where g is the gap between the developer and PC surface and η_x is the feature size dependent factor defined by

$$\eta_x = (\eta_{x,max} - \eta_{x,min})w + \eta_{x,min}. \quad (9)$$

The two phenomenological factors $\eta_{x,max}$ and $\eta_{x,min}$ are empirically adjusted from measurements for different print engines using the calibration pattern in Figure 5. The feature size parameter w at (x, y) is obtained from the horizontal field $E_x(x, y, z_0)$, using the anti-symmetry of E_x.[3] As illustrated in the next section, selecting a different value for z_0 makes little difference in final DMA and requires adjusting $\eta_{x,max}$ and $\eta_{x,min}$ accordingly. Calculation of horizontal displacement in the y-direction can be carried out similarly. More physically detailed treatments of particle simulation can be found in other publications.[4,5]

Our development model accounts for the "funneling" effect from the horizontal fields and AC bias by calculating horizontal displacement (x', y') at each (x, y) and adding the base DMA at (x, y) to the final DMA at (x', y').

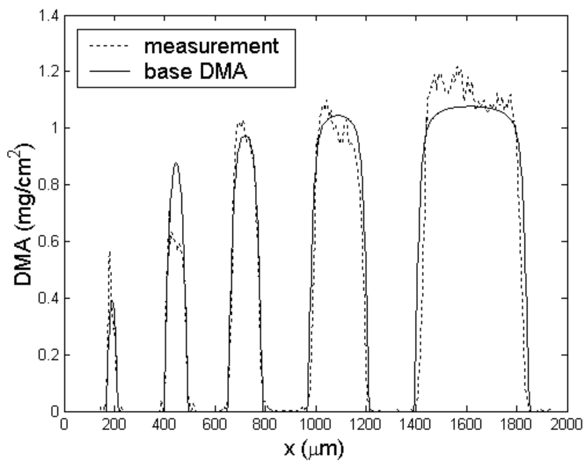

Figure 4. Base DMA (1200 dpi). Note the excess line widths

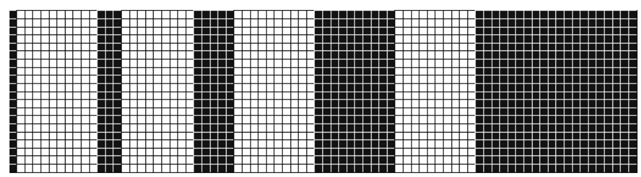

Figure 5. Vertical lines of varying widths

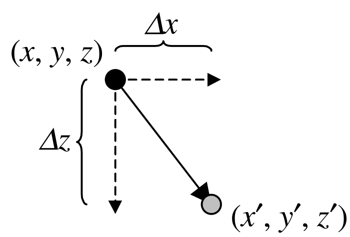

Figure 6. Single particle displacement

Simulation and Measurements

We verified our phenomenological approach using two different printers: a 600 dpi printer and a 1200 dpi printer. The base DMA shown in Figure 4 was obtained using the parameters of the 1200 dpi printer. Figure 7 shows the DMA of the bitmap in Figure 5, using $z_0 = d + 50$ µm, $\eta_{x,max} = \eta_{y,max} = 0.25$ and $\eta_{x,min} = \eta_{y,min} = 0.0$, which is in good agreement with the measurement. The corresponding (inverted) gray level plot is shown in Figure 8. Figures 9 and 10 show the DMA when z_0 is set to $d + 10$ and $d + 70$ µm, respectively. Comparing these results with Figure 7, we note that the results are virtually identical. From this we conclude that the calculation is insensitive to z_0 within about 20% of the gap length from the photoconductor surface. Using the same bitmap at 600 dpi, we simulated the 600 dpi printer and the resulting DMA is shown in Figure 11, where $z_0 = d + 50$ µm and the phenomenological factors $\eta_{x,max}$ and $\eta_{x,min}$ are set to 0.45 and 0.15, respectively (same in the y-direction).

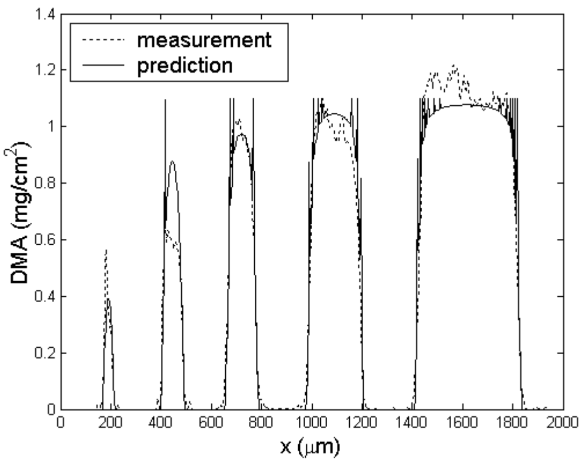

Figure 7. DMA (1200 dpi) with z_0 = d + 50 μm. The predicted widths are in good agreement with the measurement for all line widths in the calibration pattern

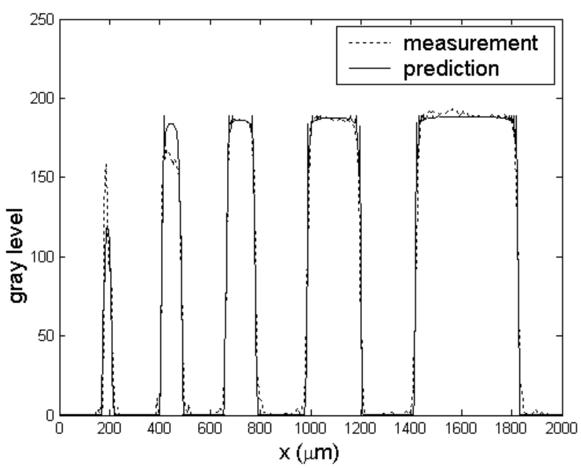

Figure 8. Gray level (1200 dpi) with z_0 = d + 50 μm

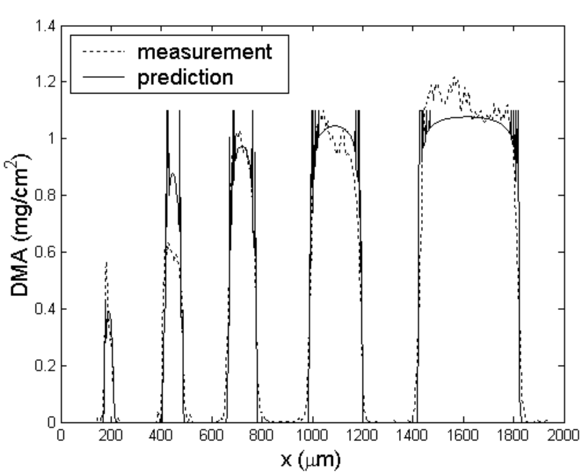

Figure 9. DMA (1200 dpi) with z_0 = d + 10 μm

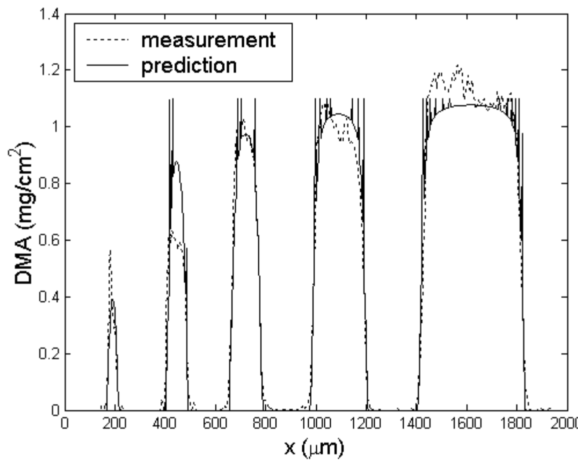

Figure 10. DMA (1200 dpi) with z_0 = d + 70 μm. Changing z_0 makes little difference in line widths

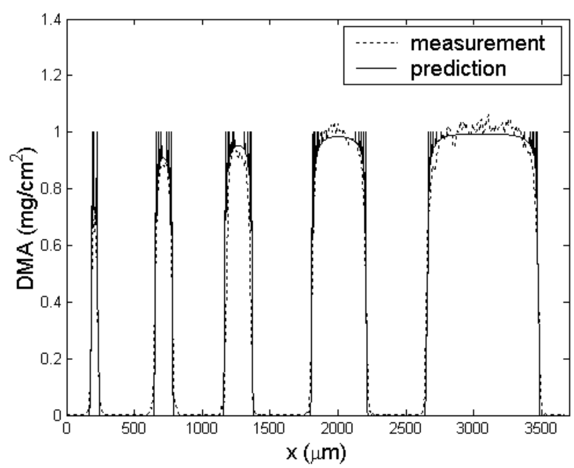

Figure 11. DMA (600 dpi) with z_0 = d + 50 μm

Our development model can estimate the darkness of any bitmap. Using the 600 dpi printer parameters and the bitmap in Figure 12, the predicted DMA and gray level are shown in Figures 13 and 14, respectively. Figure 15 shows the scanned grayscale image and predicted grayscale image of the same bitmap. Using the 1200 dpi printer parameters, the predicted grayscale images and scanned images of a 4-point "w" character and a 1.2-point "p" character are shown in Figures 16 and 17, respectively. The bitmap of the "p" consists of single pixel wide lines as shown in Figure 18. The model predictions are in good agreement with the measured grayscale values.

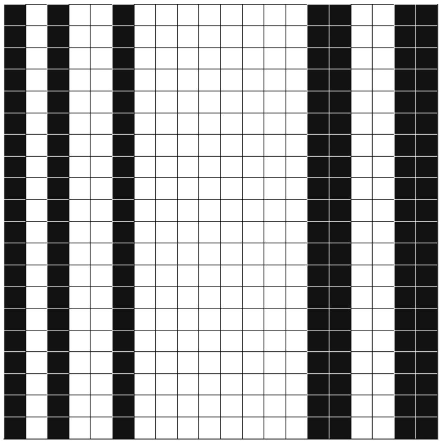

Figure 12. Bitmap of several lines

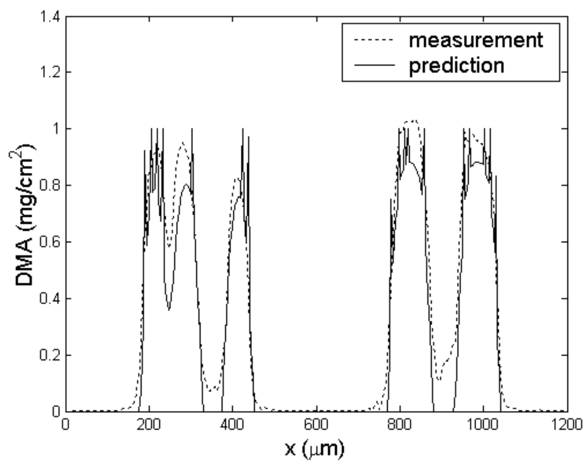

Figure 13. DMA (600 dpi)

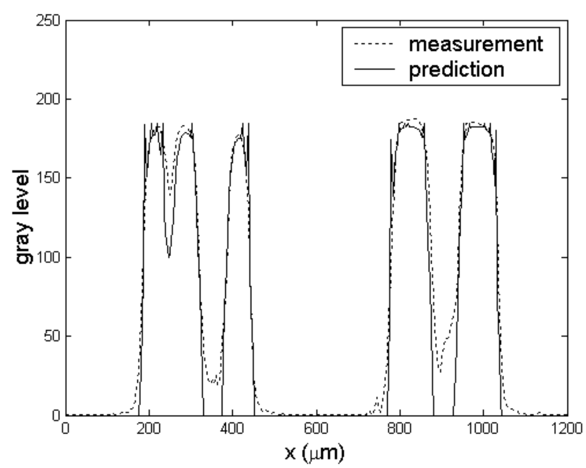

Figure 14. Gray level (600 dpi). The measured gray level in this figure and the measured DMA in Figure 13 display approximately half a toner layer of development on the average between the lines. This is primarily due to toner scattering (see Figure 15)

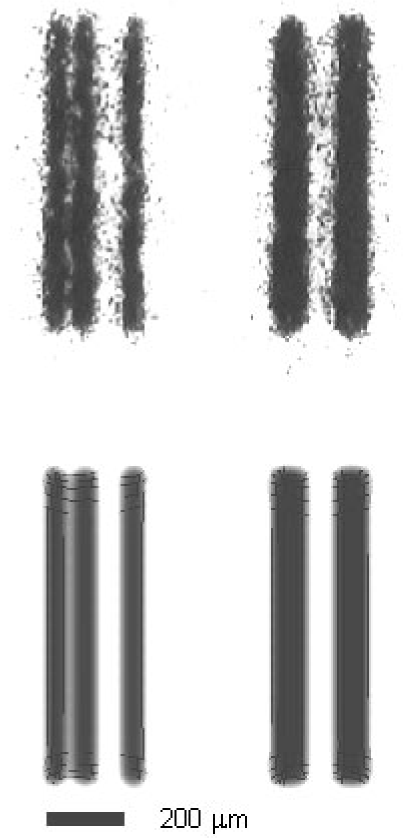

Figure 15. Grayscales for 600 dpi: measurement (top) and prediction (bottom). Note that the predicted grayscale image is free of toner scattering

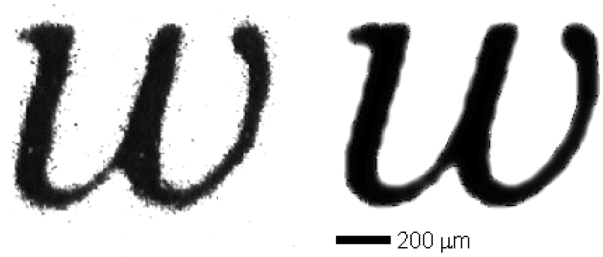

Figure 16.Grayscales for 1200 dpi: scanned 4-point "w" (left) vs. predicted "w" (right)

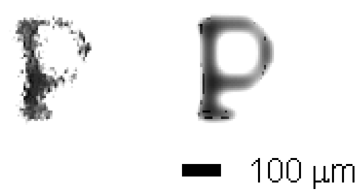

Figure 17. Grayscales for 1200 dpi: scanned 1.2-point "p" (left) vs predicted "p" (right)

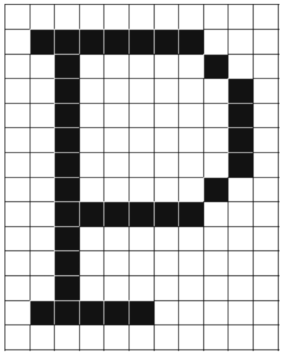

Figure 18. Bitmap of "p"

Conclusion

We demonstrated how normal and horizontal fields can be used to estimate gray level and developed mass per unit area (DMA) of an arbitrary bitmap. The estimation procedure is phenomenological. It exploits the physics governing toner movement in the development nip to account for observed feature size dependence of toner development. Estimated DMA specifies developed mass at each point in the calculation grid. Thus, for any input bitmap, DMA at the subpixel level can be accurately predicted over the entire image.

Using two test printers, we verified our phenomenological approach. The phenomenological expression does not change its form when a new test device is introduced; the phenomenological parameters are merely recalibrated accordingly.

Acknowledgement

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References

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Biography

Jang Yi received his B.S. degree in computer engineering from the University of Idaho in 1997 and a M.S. degree in electrical engineering in 1999. He's currently a Ph.D student at the same institute. His thesis was on designing an electrophotographic simulation tool. His current research area is the development process.