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A Direct Current-Jump, Nonmagnetic, Monocomponent Electrophotographic Development System[1]

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Abstract. *A new monocomponent electrophotographic development system is introduced, in which nonmagnetic toner jumps the gap between the development roller and the photoreceptor only under the influence of the direct current electric fields of the latent image. This development system requires for its operation low toner adhesion, which is achieved by a patented toner formulation. Such a development system is ideally suited for a small size, low cost, color electrophotographic engine. A prototype color printer utilizing this unique development system in an image-on-image architecture has been implemented to demonstrate its printing capabilities. Photomicrographs of print samples are shown and the scalability and extendibility of this technology are discussed. © 2006 Society for Imaging Science and Technology.*
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INTRODUCTION

Of the many monocomponent electrophotographic development systems that have been invented and are commercially available,[1] one is conspicuous by its absence: a direct current (dc)-jump monocomponent development system. In this development system insulating, nonmagnetic toner jumps the gap between the development roller and the photoreceptor only under the influence of the dc electric fields of the latent image. Commercially available monocomponent development systems use either contact between an elastomeric development roller and the photoreceptor or alternating current (ac) electric fields across the development gap.

The reason a dc-jump development system has not been made operational is well-known: the Coulomb forces due to the dc electric fields of the latent image are much smaller than the force of adhesion between the toner and the development roller. Therefore, the Coulomb forces are insufficient to cause the toner to move from the surface of the development roller to the surface of the photoreceptor. In commercially available development systems toner adhesion is unimportant. This is because the use of contact cancels toner adhesion because toner-adhesive forces occur to both sides of the toner particle. The use of ac electric fields eliminates toner adhesion as a development parameter because the toner is released from the development roller surface by the ac fields. Prior attempts to make this dc-jump system operational include (1) "spaced touchdown," in which a development roller was spaced 25–50 μm from a photoreceptor surface (see Sec. 9.2 in Ref. 1); (2) a system in which a metal development roller was loaded with toner by powder cloud deposition techniques and then corona charged (see Sec. 9.2 in Ref. 1); more recently, (3) an early color electrophotographic engine called the Panasonic FP-C1 (see Fig. 11.12 in Ref. 1, and references therein); and (4) a Moore system[2] in which ion charged toner is loaded onto a donor roll and then transferred with dc fields onto a photoreceptor at close spacing. The early systems were never commercialized almost surely because of poor control of the toner charge distribution; the Panasonic and Moore systems were withdrawn and have not been reintroduced.

The critical hurdle that must be overcome to make this development system viable is to reduce the toner adhesion so that the Coulomb forces due to the latent image are greater than the toner adhesion force. Unfortunately, toner adhesion has been shown experimentally to be very high, at least ten times higher than expected from simple theory which is based on image force calculations that assume a charged toner particle can be represented by putting the total charge in its center. Theories have been suggested to account for such high toner adhesion,[3,4] but they did not lead to suggestions for significantly reducing toner adhesion.

Recently, significant advances have been made both theoretically and experimentally in the area of toner adhesion.[5,6] Based on the concept that toner adhesion is determined by the electrostatic proximity force, toners have been designed with much lower adhesion than available before and a theoretical explanation has been suggested to account for these data. As will be shown below, these advances have now made a dc-jump monocomponent development system viable.

This noncontact development system allows image-on-image (sometimes called tone-on-tone) architecture, i.e., the toner images can be accumulated on the photoreceptor. Such an architecture allows the design of a minimum volume electrophotographic engine since it eliminates the need for intermediate transfer drums or belts or structures to ac-

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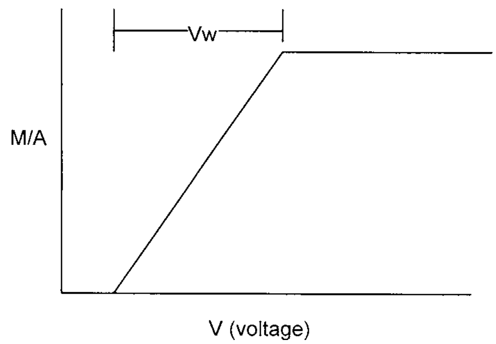

Figure 1. Monocomponent development systems can be characterized by a voltage width. On the vertical axis is the developed mass per unit area (M/A). On the horizontal axis is the applied voltage (at a fixed gap, L). The voltage width V_w is defined as the difference between the saturation and threshold voltages.

cumulate the toner images on paper. Therefore, this development system is ideally suited for the design of the smallest size and the lowest cost color electrophotographic engine.

The iGen3 system manufactured by the Xerox Corporation also has an image-on-image architecture. However, it does not use a dc-jump development system. Instead, on the development roller surface is placed a thin wire to which ac electric fields are applied to overcome the toner adhesion. Then the dc fields of the latent image collect the toner. Also, this system does not use the natural limit of the toner on the development roller to determine the maximum toner development. Instead feedback systems are used to control the maximum amount of toner development.

Discussed below are the requirements and characteristic of this new development system along with photomicrographs of print samples.

REQUIREMENTS OF A DC-JUMP, NONMAGNETIC, MONOCOMPONENT DEVELOPMENT SYSTEM

Description

This development system is identical in structure to many of the commercially available nonmagnetic toner, monocomponent development systems: it has a foam supply roller, an elastomeric doctor blade, and an aluminum development roller. The uniqueness lies in the design of the toner particles, which are optimized for low toner adhesion, as discussed below.

In this development system, there is a gap between the development roller and the photoreceptor. The electric fields of the latent image attract the toner from the surface of the development roller to the latent image on the photoreceptor. Therefore, the electric field which determines toner development is not the electric field at the surface of the photoreceptor, as in other development systems, but instead, is the electric field at the surface of the development roller. The quantification of the electric field at the surface of the development roller requires a three dimensional solution of Poisson's equation, which is determined by the detailed structure of the charge pattern on the photoreceptor, i.e., the detailed structure of the latent image. Familiar concepts of toner development, such as enhanced line edge effects due to fringe electric fields at the surface of the photoreceptor, need to be replaced with concepts of toner release from the surface of the development roller and the toner particles following electric field trajectories to regions of the photoreceptor where the electric field is attractive. This has some similarities to powder cloud development (see Sec. 9.1 in Ref. 1) which produced some of the crispest, cleanest images with the highest resolution in electrophotography.

In order to understand and quantify toner adhesion requirements, consider solid area development. Low toner adhesion is the most critical requirement of this new development system. For a dc-jump development system to be viable, the Coulomb force QE due to the latent image must be larger than the toner adhesion F_a

$$QE = Q\frac{V}{L} > F_a, \qquad (1)$$

where Q is the toner charge and E is the electric field due to the latent image. For solid area development E equals V, the potential difference between the image area on the photoreceptor and the development roller, divided by L, the gap between the photoreceptor and the development roller. Typically V is 700 V and gaps of 150–400 μm are used in commercially available electrophotographic engines.

Toner adhesion is a distributed properties because of the many toner particle diameters and charges within any toner sample. Toner adhesion can be characterized by its voltage width V_w in monocomponent development systems, as described below.

Voltage Width

It has been found that toner adhesion, because it is a distributed parameter, can be characterized by a concept called the voltage width. The voltage width (see Fig. 1 and Fig. 9.6 in Ref. 1) characterizes a measurement of the development of toner in a monocomponent system. On the vertical axis is the developed mass per unit area (M/A). On the horizontal axis is the applied voltage (at a fixed gap, L). This curve, for any monocomponent development system, has a voltage threshold, rises, and then saturates when all of the toner is removed from the development roller. The voltage width V_w is defined as the difference between the threshold and saturation voltages. The saturation voltage V_s represents the maximum toner adhesion (which is approximately equal to V_w if the threshold is small). The maximum toner adhesion F_a(max) is the equal to the toner charge times the electric field E in the gap at the saturation voltage (which equals the saturation voltage divided by the gap used in the experiment), i.e., $F_a(\text{max}) = QV_s/L = QV_w/L$, assuming zero threshold voltage.

When the voltage width V_w is less than V, typically 700 V, all of the toner is developed and a dc-jump monocomponent system becomes viable. If one considers an image-on-image architecture, one must take into account the voltage drop across already developed toner layers. This turns out to be about 100 V per toner layer. Therefore, in-

Table I. Toner adhesion measurements taken from the literature (see Ref. 3) (the first four columns) and a calculation of the voltage width V_w (the last column), see text.

Diameter (μm)	Q/M (μC/g)	Adhesion calculated (nN)	Measure (50%) calculated ratio	V_w (at 150 μm) (V)
20	5	17	47	11400
20	10	68	29	14100
20	30	610	7	10200
10	12	6.6	45	14200
10	5	1.2	36	4950
10	8	4.6	12	3950
10	16	12	12	5160

order to develop three toner layers, a V_w of 400 V is required (which takes into account the voltage drop across two already developed toner layers and leaves 100 V for tolerance allocation).

The 400 V V_w toner requirement is based directly on the available voltage of commercially available organic photoreceptors, about 700 V. It is well-known that this limit is determined by internal dielectric breakdown within the organic photoreceptor. Therefore, this voltage can be increased if the organic photoreceptor is made thicker, which would therefore allow the use of toner with higher adhesive forces.[7]

Toner adhesion measurements have been reported extensively in the literature. In order to provide a comparison between the adhesion of commercially available toners and the toners used in this new development system, we have shown in Table I data taken from the literature (the first four columns) and a calculation of the voltage width (shown in the last column). In the first two columns are shown the toner diameter and Q/M (charge to mass ratio). The calculated adhesion (third column) is based on the assumption that adhesion is due to the attraction of the toner charge to its image charge and that the charge of the toner is in its center. The fourth column is the ratio of the measured adhesion (at the 50% point) to the calculated adhesion. It is apparent from the table that the measured adhesion is 7–47 times larger than calculated. Virtually all prior measurements give similar answers (see Refs. 5 and 6). The voltage needed to develop this toner (V_w) is estimated in the last column. This is done using Eq. (1), assuming that the toner adhesion to develop all the toner is twice the measured adhesion at the 50% point, and using columns 1 and 2 to obtain Q. This gives the electric field needed to develop all of the toner, which can be expressed as a voltage width (V_w) at a specific gap, which we choose to be 150 μm. Note that the voltages needed are between 4000 and 14 000 V. This magnitude of voltage is much larger than has ever been achieved with any photoreceptor, as far as the authors know, and is much larger than the 400 V requirement derived above.

Low Toner Adhesion

From the above discussion, it is clear that in order to make a dc-jump monocomponent development viable, toner adhesion has to be reduced by at least one order of magnitude. As mentioned in the Introduction, significant advances have recently been made both theoretically and experimentally in our understanding of toner adhesion.[5,6] Prior thinking was that such large toner adhesion is due to nonuniform charge distributions on the surface of a toner particle. But, it has been shown[5] that a uniform distribution of charge on the surface of the toner particle, taking into account the discreteness of toner charge, also has enhanced adhesion to a conductive plane. This new force has been called the proximity force because it is due primarily to the charges in close proximity to the contact point. The value of this proximity force is $4/\pi$ times the usual image force. So the adhesion of a perfectly spherical, uniformly (but discretely) charged, insulating particle is the sum of the image force and the proximity force, or $(1+4/\pi)$ times the image force. For toners, which are not perfectly spherical (including chemically prepared toners) the proximity force is active at each contact point n, so the total electrostatic adhesion is $(1+4n/\pi)$ times the image force. Obviously for large n, the data shown in Table I can be accounted for. Also, it is clear that to minimize toner adhesion, one must minimize n, the number of contact points.

The key to achieving low toner adhesion is to realize that the number of contact points can be controlled by the extraparticulate formulation.[8] In this new formulation the amount of extraparticulates is about 1 monolayer, larger than is usually used. Our picture is that we have created a particle with uniform, small protrusions around the surface which when contacted to a plane, only makes contact at a minimum number of protrusions.

In Ref. 6 data on 16 μm diameter toner were shown. The proximity theory of toner adhesion has actually only one free parameter, the number of contact points. When the theory was fit to the experimental data, the number of contact points turned out to be distributed uniformly between 1 and 3. We physically interpret this as follows: three points make a plane. The number of small protrusions on the toner particles which contact the plane is normally 3; however, sometimes adjacent toner holds up a toner particle, reducing the number of contact points. This accounts for the rising part of the M/A versus voltage curve (in Fig. 1). The threshold is determined by van der Waals (nonelectrostatic) forces (see Ref. 6); experimentally the magnitude of the van der Waals forces observed are in excellent agreement with prior published results[9] obtained by a different method.

16 μm diameter toner, which were studied in Ref. 6, is too large to be of commercial interest because the quality of its images is unsatisfactory. An approximate 400 V V_w curve measured at gap of 150 μm for an 8 μm diameter toner is shown in Fig. 2. With a 400 V V_w, such a toner satisfies the

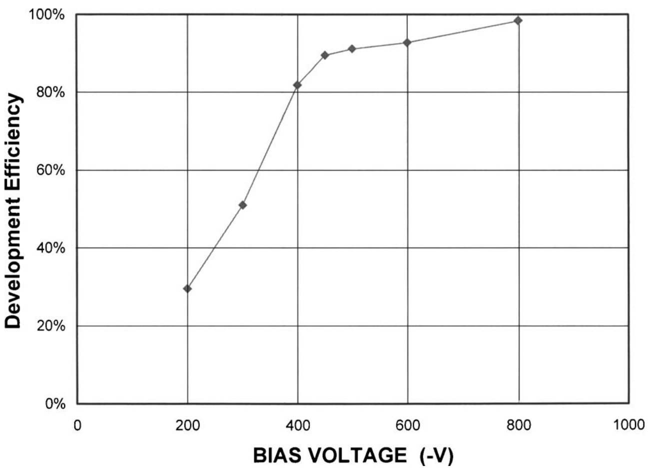

Figure 2. Development curve for an 8 μm diameter toner measured at a 150 μm gap. The V_w (see text) is approximately 400 V. Development efficiency is defined as mass per unit area M/A developed divided by the M/A originally on the development roller. At 1:1 speed ratio, the maximum development efficiency is 100%.

requirement for an image-on-image dc-jump monocomponent development system. And an 8 μm diameter toner produces satisfactory image quality and is generally used in the industry today.

Speed Ratio

This development system requires a 1:1 speed ratio between the development roller and the photoreceptor. This is because toner accumulation will occur at either the front or trailing edge of solid area images if the speed ratio is increased or decreased. Therefore, the mass per unit area on the development roller should be sufficient to produce acceptable solid area optical densities, which is approximately 1.5 monolayer for matte toner.

Gap

The gap required for a viable development system depends on characteristics of both solid area and dot development.

For solid area development, the parameters determining the gap are the values of the V_w and the toner voltage. The toner voltage V_t depends on the photoreceptor dielectric thickness, and the toner mass per unit area and charge to mass ratio (after recharge, assuming an image-on-image system is implemented), as given in Eq. (7.19) in Ref. 1. In order to develop three layers it is necessary that V, the potential difference between the image areas on the photoreceptor and the development roller, be greater than

$$V > V_w(L) - 2V_t - 100 \text{ V}, \quad (2)$$

where we have added 100 V for tolerance control. Note that V_w depends linearly on the gap L [since to achieve the required force or electric field the voltage increases linearly as the gap increases, see Eq. (1)] but V_t does not. So as the gap is increased, V_w increases until this inequality is no longer satisfied.

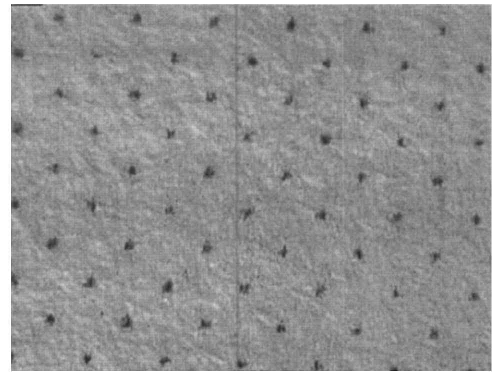

Figure 3. Images of dot development (2×2 at 600 dpi) on paper using an 8 μm diameter toner whose development characteristics are shown in Fig. 2.

For dot and line development one must determine the electric fields at the surface of the development roller that overcome the toner adhesion, which is determined by the latent image on the photoreceptor. As mentioned above, this problem requires a three dimensional solution of Poisson's equation to calculate the electric field at the surface of the development roller, coupled with a theory of toner adhesion to determine how much toner will be released from any given area of the development roller. Or experimental measurements can be made for realistic situations. Shown in Fig. 3 are dot development of an 8 μm diameter toner at a gap of 170±20 μm, with the variation determined by electrophotographic parameters. From the good quality of the dots it is clear that this gap is adequate for this 8 μm toner.

CHARACTERISTICS OF A DC-JUMP, NONMAGNETIC, MONOCOMPONENT DEVELOPMENT SYSTEM

Image-on-Image Architecture

As pointed out in the Introduction, this development system allows accumulation of the toner images on the photoreceptor, a characteristic that is not possible with development systems that use contact, because contact will disturb already developed images, or ac voltages, because ac voltages scavenge already developed toner into the active development system causing contamination.

Image-on-image architecture has a distinct advantage. In all color electrophotographic engines the toner image must be accumulated on a surface. There are three choices, the paper, an intermediate drum or belt, or the photoreceptor. Accumulation on a belt photoreceptor allows for the smallest possible volume of any electrophotographic engine.

Scalability and Extendibility

Due to the image-on-image architecture, this technology can be adapted to 1-pass, 2-pass, or 4-pass architectures in order to meet the performance requirements of various market segments.

For the small office, home office market, a 4-pass architecture provides small size and low cost advantages. We expect that a color electrophotographic engine that uses this dc-jump system can have a volume very close to that of a

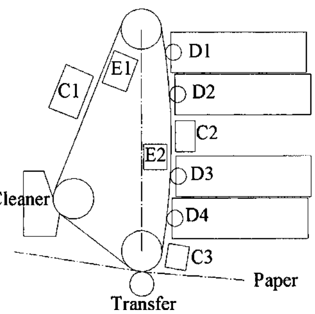

Figure 4. Schematic of a 2-pass electrophotographic engine using image-on-image architecture allowed by this new dc-jump development system.

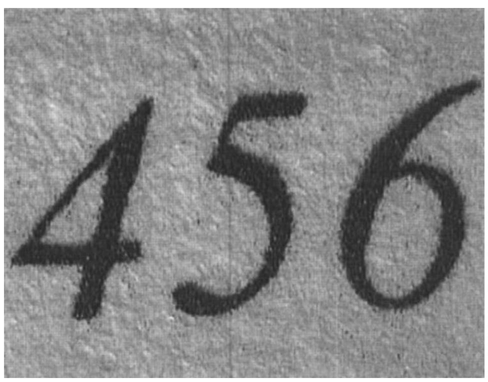

Figure 5. Images of eight-point font on paper using an 8 μm diameter toner whose development characteristics are shown in Fig. 2.

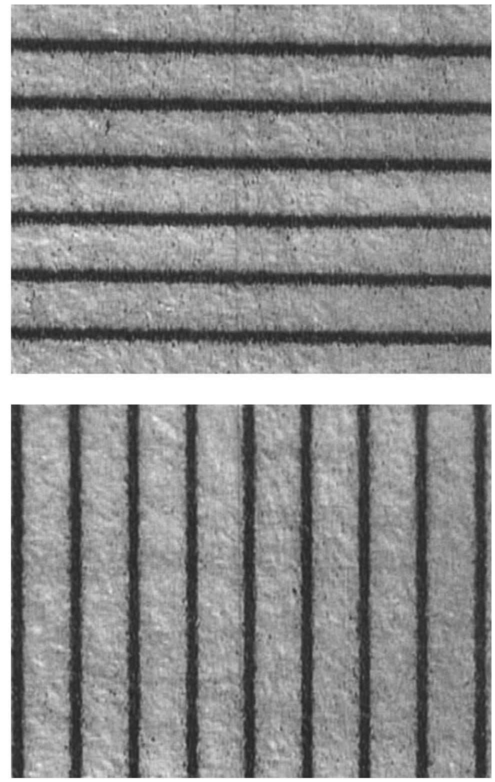

Figure 6. Images of horizontal and vertical 2 pel (300 dpi) lines on paper using an 8 μm diameter toner whose development characteristics are shown in Fig. 2.

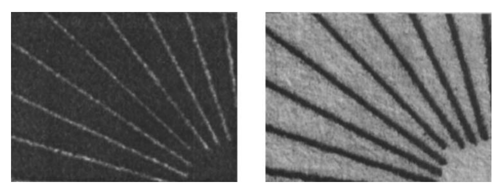

Figure 7. Images of white and black 300 dpi lines at various angles on paper using an 8 μm diameter toner whose development characteristics are shown in Fig. 2.

black and white electrophotographic printer with the addition of three extra color toner cartridges. We have estimated machine volumes of 27 l for a 4-pass architecture, which is less than 50% of the volume of the current commercially available color electrophotographic engines. Prototypes have been designed with throughput speeds of 15 ppm for mono and 4 ppm for color.

With the minimal cost of one additional charging and imaging subsystem placed between the second and third color development systems, a 2-pass engine can be designed, as shown in Fig. 4. During the first pass the OPC is charged $C1$, exposed $E1$, developed $D1$ and then charged $C2$, exposed $E2$, and developed $D3$ again. During the second pass $D2$ and $D4$ are active. Finally, the toner layers are recharged $C3$ (see the Toner Recharge section), transferred, fused on paper (not shown), and the OPC is cleaned. The images shown in Figs. 3 and 5–7 were made on this Aetas built engine. Using a 2-pass engine the color output speed is increased by a factor of 2, to 8 ppm for color. For highlight color (2-color) printing, such as in letter head and bank statements, a 2-pass engine delivers 2-color prints with the same speed as the monochrome prints, 15 ppm.

For applications in the general office which demand fast color output, a 1-pass architecture is an option to meet the market requirements. With increased process speed, the system has been experimentally proven capable of reaching 27 ppm for both mono and color printing. From the point of view of the development system, there does not appear to be limitations to the process speed. This is shown as follows: The time it takes the toner to move from the development roller to the photoreceptor is $L\{2/[V(Q/M)]\}^{1/2}$. Assuming $L=170\ \mu$m, $V=400$ V, and $Q/M=10\ \mu$C/g, this is 0.12 ms, about 100 times faster than any point of the photoreceptor is in the development zone. We expect that process speeds will be limited by engineering issues, such as thermal and ozone ventilation and toner supply.

One Transfer Step

This system also has the advantage that all images accumulated on OPC are transferred to the paper in one step. There is no need for four transfers, which must be done with accumulation on paper, or four transfer to an intermediate surface and then one transfer to paper.

Toner Recharge

In an image-on-image architecture each toner layer except the last is recharged by the next charge-expose-develop step. This recharge step significantly raises the toner charge-to-mass ratio, which reaches saturation within one recharge. But the last developed toner layer is not subject to recharge and its charge is much lower. This produces unsatisfactory transfer of the last toner layer. To ensure that all toner layers have the same charge-to-mass ratio, a pretransfer recharge step (*C*3 in Fig. 3) is implemented which is identical to the other recharge steps.[10]

Registration

Registration is close to ideal because the toner images are built up on the photoreceptor surface. Encoding systems can easily track the position of the photoreceptor, compensating for the effects of motor instabilities and therefore allowing high registration accuracy, limited only by the small amounts of horizontal (cross process) photoreceptor walking.

Development Roller Bias and Background Development

Zero electric field produces zero force on the toner. While this may sound obvious, the implication is that the development roller bias should be set equal to the background potential. This has two advantages. It allows the most efficient use of photoreceptor potential of any electrophotographic development system. For all other development systems the development roller bias is set between the background and image potentials to provide a reverse bias to limit background development. Second, this biasing scheme naturally limits background. Zero force also will not attract toner into the background regions of the photoreceptor.

Contamination Elimination

For an image-on-image system toner contamination can be a concern. Consider a developed toner layer going underneath an inactive development roller. The developed toner on the photoreceptor is at a potential of −150 V (−50 V residual on the photoreceptor plus −100 V due to the toner voltage). After imaging for the second toner layer some of this toner will be at −750 V (nonimage areas) and some will be at −150 V (image areas). There is no development roller potential which will not cause contamination either towards the development roller or towards the photoreceptor. However, if the inactive development roller is electrostatically cleaned of toner prior to the photoreceptor with developed toner entering into this inactive development system, contamination is eliminated without sacrificing print quality or productivity.[11]

Other Subsystems

For small size and low cost, we have found it advantageous to use a light emitting diode array instead of a laser scanning system for exposure. In addition, we implemented a new, novel charging system, called a capatron,[12,13] which is smaller than a scorotron, and has self-cleaning characteristics.

PRINT SAMPLES

Several photomicrographs of images on paper produced by this new developed system are shown in Figs. 3 and 5–7. All of these images were made with an 8 μm diameter toner with the V_w shown in Fig. 2 with the Aetas built 2-pass engine discussed above (see Fig. 4). In Fig. 3, note the good quality of the 2×2 dots (at 600 dpi): their shape and size is very uniform. Note the low toner scatter around the dots and the very low background observed. These dots are fully developed with toner. Figure 5 shows text made of an eight-point font. Background is again very low and toner scatter around the edges (called edge raggedness) is low. The characters are crisp and easily readable. In Fig. 6 are shown horizontal and vertical 2 pel (300 dpi) lines, in which the background is low, the edge raggedness is low, development is good, and the line width is approximating equal for both the horizontal and vertical lines.

A unique feature of this development system is that identical small white and black images are approximately equally visible on the printed page (see Fig. 7). The explanation for this feature comes from a consideration of the electric fields responsible for white and black images. While the latent image of a small white image is weaker than the identical small black image, as in any "write-black" system, the white image has the advantage in this development system because it is takes a smaller latent image to repel toner from the surface of the photoreceptor than it takes to attract toner from the surface of the development roller.

SUMMARY

A new monocomponent development system has been made operational and tested inside an electrophotographic printer. The development system is a dc-jump, nonmagnetic, monocomponent development system. It requires for its operation low toner adhesion which was achieved with a patented extraparticulate formulation.[8] This new development system is ideally suited for a small size, low cost, color electrophotographic engine.

Using this new development system, a printer has been implemented in an image-on-image architecture, in which all color toner images are accumulated on the photoreceptor before transferring to paper. It is believed that with the use of this development system, a minimum volume color electrophotographic engine can be made: we estimate 27 l, less than 50% of the volume of currently available engines.

In order to implement this new development system into an image-on-image architecture, several subsystem interactions need to be understood and optimized. The last toner layer needs to be recharged prior to transfer to eliminate toner layers of different charge-to-mass ratios entering into the transfer subsystem.[10] And contamination of inactive development systems can be eliminated by electrostatically cleaning the development rollers prior to use.[11]

Photomicrographs of images on paper made with this development system are shown and compare favorably with the best images available in electrophotography today. Images of 2×2 dots, eight-point type and 2 pel (300 dpi) horizontal and vertical lines are shown. These images are fully developed, have low edge raggedness, and have low background. A unique feature of this development system is small black and white images are approximately equally visible on the printed page.

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