The Impact of Digital Xerography on Marking Materials

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Abstract

For the past forty years, light-lens copiers have been the dominant form of xerographic imaging. However, recent rapid progress in digital software and hardware has now enabled xerographic imaging to evolve to a digitally-based printing technology for both full-color and black-and-white applications. As a result, many of the limitations imposed by light-lens imaging have now been removed via digital software applications in areas such as image processing and process control. From a marking materials viewpoint, however, many of the opportunities and challenges posed by digital imaging are yet to be addressed, since current xerographic toners and carriers are still largely based on design concepts that were developed for the mature technology of light-lens imaging.

Introduction

The advanced product development process has been compared to the game of pinball (*pachinko*) — in both cases, the reward for success is the chance to repeat the process.[1] In R&D as a result, experienced technologists form the essential core of any product development team, and most product planning staff management team members are former R&D line managers and senior technologists. In this way, past hard-won knowledge and experiences can be directly incorporated into future planning and R&D activities, and for gradual (*kaizen*) improvements in technology this is an efficient process.[2] However, for cases where the future R&D activities involve new technologies, there is a danger that past experiences may inappropriately influence future plans and strategies. In a sense, the actions of experienced product planners and R&D technologists may match those of "politicians (who) have the same occupational hazards as generals — focusing on the last (i.e., previous) battle and overreacting to that".[3]

The above considerations are most significant in R&D activities involving major changes in technology — in such cases, past experiences may be quite irrelevant to the new challenges and may hinder the strategies needed for future success. In the field of commercial xerographic imaging, there have been several major advances in technology during the past 40 years, but the present-day transition to digital imaging certainly imposes challenges and opportunities well beyond the scope of past experiences and technologies. For example, while digital imaging can provide software solutions to many difficult imaging quality issues, it also imposes a new set of requirements on imaging hardware and consumable marking materials. To illustrate some of the important effects of the analog-to-digital xerographic transition, key features of pre- and post-digital dry toner-based marking materials will be briefly compared and contrasted in the following sections of this present report.

Dry Toner-based Marking Materials for Analog Imaging

In the 1960's, light-lens-based office copiers achieved significant commercial success. Such products were based on the cascade mode of development, with carriers of 200 micron diameter or greater, and toners of 12 micron or greater. A simple toner design — carbon black, melt-mixed into thermoplastic resin — provided the necessary negative toner polarity for charged-area imaging on selenium and selenium alloy photoreceptors. Since the cascade mode development responds chiefly to steep gradients in the latent electrostatic image, it was well-suited for the development of simple line text at a legible density in early xerographic copiers. The maintenance of image quality via periodic manual adjustments to the toner supply rate of such copiers was enabled by two complementary features of the developer materials and the development mode — (a) the toner charge-to-mass ratio, ***q/m***, was almost a direct inverse function of the toner concentration, *C*, and the developed line density was almost a direct inverse function of ***q/m***, so that line density could be simply altered via changes in the amount of toner added to the developer; (b) as the developer aged, the ***q/m***:*C* relationship steepened with the net result that an adequate image density could be maintained even as long-term copying tended to reduce the toner concentration. From a present-day viewpoint, of course, the image quality and stability of cascade development was quite variable, and end-of-life failure could occur quite sporadically.

In the 1970's, cascade development was replaced by insulative magnetic brush (IMB) development, and this led to a minor reduction in toner size and a more significant reduction in carrier size. At low process speeds or in multiroll configurations, this new mode of development reproduced solid-area images in addition to fine lines. Though toners were still chiefly negative polarity, based on simple melt-mixtures of carbon black and resin, one significant change in toner design was the reduction in fine particle content via selective classification — this change reduced the rate at which toner contaminated the surface of the carrier beads[4] (and hence the rate of decline in the triboelectric charging ability of the xerographic developer), and improved the usable life of xerographic developers by about a factor of ten. Another significant improvement in quality was achieved via simple closed-loop control of the image density, with feedback to the toner dispenser. As a result, stable imaging was achievable over a wide range of usage-induced developer "ages".

While the emphasis in the USA was towards high-speed copiers and duplicators, the initial focus for Japanese manufacturers was aimed at compact desktop products. To enable reduced power operation and low noise levels, these Japanese products were typically designed to operate with "oil-free" fusers, and blade-cleaned photoreceptors. To enable these process changes, toner designs became more complex: a synthetic or natural wax (to provide the necessary release from the oil-free fuser roll) was added as an internal component, and sub-micron silica particles and fluoropolymer particles were blended onto the toner surface to enhance powder flow and to promote effective blade cleaning of the photoreceptor.

Another significant development driven by the needs of the Japanese market was the introduction of compact copiers based on toner-only single component development (SCD).[5] In this carrier-free mode, a thin layer of toner is applied to a donor roll, and an AC/DC bias is used to stimulate noncontact development across the donor roll–to–photoreceptor gap. For black imaging, an SCD toner is typically loaded with a high level of magnetite (to provide a magnetic attractive force between the toner particles and the donor roll, and thereby create a stable toner layer), and a charge control agent (CCA) is added to the toner design to enhance triboelectric charging in the toner layer-forming step. Internal and external additives such as wax and fumed silicas are also typical components of SCD toners.

In the early 1980's, the development of organic photoreceptors necessitated a change to positive toner polarity for light-lens xerographic products, and this stimulated the development of many positive CCA's from a variety of chemical classes. Coincidentally, the conductive magnetic brush (CMB) mode of development was utilized in several high-speed copier/duplicators. This mode of development provides a high rate of image development coupled with a strong suppression of background, and an additional noteworthy feature of certain positive polarity CMB developers is a zero long-term rate of tribo aging.[6,7] (For a final generation of selenium photoreceptor-based copiers, CMB developers were also designed with negative toners blended with zinc stearate to enhance developer packing and hence developer conductivity).[8]

In the late 80's, new "agitated development zone" modes of development enabled high levels of development from IMB developers,[9,10] and this led to new CCA-based positive toners coupled with well-coated insulative carriers. In certain toner designs, magnetite was added as an internal component to provide magnetic forces for the control of background development. To enable the use of such designs in compact copiers, a trickle" mode of developer replacement was utilized. In this mode, a small aliquot of new carrier beads is continually added to the working developer (i.e., toner-rich developer is used in place of dispensed toner), and a corresponding amount of "aged" developer is drained from the development housing — the net effect at equilibrium is a zero rate of carrier aging, and hence stable xerographic imaging.[11]

Dry Toner-based Marking Materials for Digital Imaging

The initial transition from analog to digital xerography merely involved a direct replacement of document exposure lamps by a raster-scanning laser, with non-image background image areas on the photoreceptor being photodischarged by the laser beam. In this way, image areas on the photoreceptor could be developed using existing developer materials in a charged-area development (CAD) mode.[12] As a result, early digital xerographic systems did not require any additional toner/developer R&D efforts. Indeed, since digital imaging provided an increased stability in the latent electrostatic image (especially in the difference between image and background areas), digital imaging actually enhanced the xerographic performance of existing developers. From a toner/developer viewpoint, therefore, the early experiences in the analog/digital transition all appeared to be beneficial. As a result, many existing designs for TCD and SCD materials were directly applied to digital xerographic printers, especially for the output of black-only text and simple graphic images. However, despite pre-printing electronic adjustments, the output images from early digital xerographic printers still retained characteristic light-lens image defects such as incompletely-filled and ragged lines, and fluctuations in image density. Accordingly, demands for improved digital xerographic imaging performance soon provided new and challenging goals for toner/developer R&D efforts, and design requirements far in excess of past materials designs have now evolved to keep pace with the new and novel marking subsystem designs that are aimed specifically at digital applications.

In particular, the image quality and stability requirements of full-color digital xerographic imaging has created greatly increased standards for toner/developer and marking subsystem performance. Initial color products such as CANON's CLC-1 and Fuji Xerox's A-Color achieved markedly improved imaging performance via a combination of a novel mode of TCD coupled with specifically-designed toner/developer materials, and recent "tandem" applications of this technology have enabled full-color xerographic printing at 60 prints per minute. In these TCD machines, an AC/DC development bias (such as was previously employed only in SCD devices) is applied to a thin brush of a toned carrier based on small ferrite beads. From a toner design viewpoint, the effect of the various colorants on q/m is balanced via a combination of internal and external additives, and this complexity coupled with a reduced toner size has created an overall design distinctly different from those developed for past analog imaging applications. A change from charged-area development, CAD (the only mode possible with light-lens imaging) to discharged-area development, DAD (where the digital imaging light source discharges the photoreceptor in image areas) has created a further major change in toner/developer design, namely polarity. (For organic photoconductors, the CAD mode of development requires a positive polarity toner, while the DAD mode requires a negative toner). Thus, a change to the CAD imaging mode has necessitated a renewed emphasis on negative polarity charge control agents, to replace positivetoner/carrier design rules and experiences gained during the OPC/light-lens analog imaging era.

Digital xerographic imaging has now been implemented in a wide range of printers and scanner/copiers, with growth since the 1990's being stimulated by the ever-increasing emphasis on digital storage/retrieval and output from PC's and workstations. In the digital xerographic imaging era, continued increases in image quality and stability requirements are providing major new performance goals for xerographic toner/developers, and it is in such areas that the clearest distinction can be made between toner/developers for analog and digital applications. It is also in such areas where past experiences may offer little guidance for future materials R&D activities.

Since high quality offset-lithography, ink-based printing is commonly taken as the ultimate benchmark for image quality,[13] it is instructive to compare and contrast key aspects of this well-established, traditional printing technology[14] with xerographic digital imaging. Compared with offset-lithography, conventional xerographic images lack edge sharpness, and image uniformity. One simple conceptual means to minimize "noise" from xerographic images would be development from a magnetic brush that is out of contact with the photoreceptor.[15,16] However, such an approach, in addition to creating a reduced level of developability, would effectively eliminate several otherwise positive attributes of brush development — e.g., beneficial scavenging of toner from non-image areas, and control of otherwise divergent fields in the latent electrostatic images.

With respect to other potential sources of edge raggedness in xerographic images, the high overall quality of developed images on the photoreceptor versus that on the final print indicates that post-development processes must also be viewed as potential sources of image degradation.[17] Heat-assisted transfer has been proposed as an engineering approach for minimizing toner scatter from post-development images.[18] However, unlike conventional electrostatic transfer, where imaged toner is selectively transferred, the non-selective nature of any heat-assisted transfer process would likely translate back into a requirement for increased selectivity in the development process and thence in the triboelectric properties of developer materials.

Images printed with offset-lithography are considerably less raised (above the paper print surface) than those created xerographically, and this distinction is most pronounced in multilayer, full-color pictorial applications.[19] To reduce the pile height of xerographic images, toner size has been steadily reduced from 12 micron to a current state-of-the-art size of 6 micron. Initial reductions were achieved via incremental improvements in dry-grinding/classification processes.[20] but the latest reductions are based on the socalled chemical-toner processes. Thus, for its Color imageRUNNER C2058 color copier,[21] CANON has introduced waxy, suspension-polymerized S-toners,[22] while Fuji Xerox has utilized an emulsion/aggregation polymerization process[23] for waxy toners in its DocuCentre Color 400 CP printer.[24] In both cases, the final toner particles are much rounder and smoother than conventionally-ground toners, and provide a high degree of post-development transfer efficiency in addition to a low total toned image height.

In all cases involving small toners, a variety of external additives are used to enhance overall toner performance (flow, charging, transfer, humidity sensitivity etc.), and this increasing complexity in toner designs is yet another incidental effect driven by the analog-to-digital imaging transition. Since such additives may synergistically affect various toner properties, changes in additive content (e.g., as might be created via mechanical stresses during development) can affect the overall development process, and toner "aging" rather than carrier "aging" is probably the most important factor to be minimized in developer materials for digital applications.[25] From a materials viewpoint, toner robustness must be improved (e.g., via changes in binder resin), while "gentle" modes of development from compact developer housings must also be an enabling goal.[26] These areas for improvement, are a direct result of the analog-to-digital imaging transition, and are areas where past analog experiences are probably only partially instructive.

Returning to the topic of improved print quality, development from toned non-contacting donor rolls also represent a direct engineering solution for brush-free development. Indeed, for black-only imaging, incremental improvements in conventional SCD technology have been successfully incorporated into modern digital xerographic printers, while for full color development from toned donor rolls, several types of hybrid TCD/SCD development housings have been devised.[27,28] However, a common feature of donor roll-based development systems is the potential for supply-limited variations in development efficiency. In its simplest manifestation, the development of dark, large area images can remove toner from the donor roll at a rate exceeding the rate of replacement. Interestingly, this can also be a problem in traditional offset lithography,[29] and multiple inking rollers in printing presses are typically employed as a robust engineering solution. For dry toner operation, a rather more subtle form of reduced developability can be related to image-wise toner "aging". For example, toner particles on regions of a donor roll corresponding to non-image areas may become mechanically "aged" during multiple roll rotations, and thus show a level of developability below that of toner that is freshly applied to post-imaged areas of the donor roll — as a result, a variety of "ghost" images[30] (either "positive" or "negative") can be created by abrupt changes in the image content of a consecutive series of prints (e.g., solid text followed by large areas of light halftone). For full-color operation, any "ghosting"-type non-random variations in output density of any individual color will be readily apparent since it will affect the total color of a well-defined area on the print. Once again, toner robustness will be an attribute to be maximized for digital imaging applications, if "ghost" development is to be solved via a toner design.

Whereas early analog copying involved random text images at a low total image area of about 5%, modern digital xerographic printers must reproduce images from text to graphics over a coverage range up to about 20%. From a toner supply viewpoint then, digital imaging potentially involves a wide and fluctuating range of toner addition rates to the developer housing. However, since pending toner demand can be gauged from the incoming digital bit stream, a measure of feed-forward logic can be applied to the dispense process, thus enabling variably proportional dispense cycles. From a developer materials viewpoint, this is a beneficial aspect of digital imaging, since xerographic developers can be adversely affected by operation at either excessively high or low values of the toner concentration. (While offset lithographic printing occurs at a fixed inking rate for any single printing plate, a segmented ink supply station can be used to apply ink at a variety of rates in the process direction, in order to deliver ink in proportion to the image content on the printing plate[31] — implementation of such a scheme in any dry toner-based digital xerographic printer would be a difficult exercise in powder mechanics).

An important distinction between analog and digital development modes involves the triboelectric charging requirement for an effective set-point control of the output image. For early analog copiers, imaging latitude was typically expressed in terms of a range of toner concentrations for which the output image (for a specified image potential corresponding to a "dark" input image) equaled or exceeded a set minimum density, and the background density remained below a set maximum value. With such specifications, satisfactory image development could be achieved over a range of $\boldsymbol{q/m}:C$ pairs based on a simple process control strategy. By contrast, for pictorialquality digital xerographic printers (where set-point control is based on a digital halftone representation of a specified tone reproduction response), the allowable range of toner charge and concentration will be severely constrained. In fact, for digital stability, operation at a single, stable $\boldsymbol{q/m}:C$ pair represents the ideal case, since it removes toner-based variations from the halftone imaging process. In reality, however, there can be many sources for triboelectric variability — in addition to the previously-discussed intrinsic factors that produce long-term developer "aging" and short-term toner "aging", extrinsic factors such as ambient humidity can create major shifts in toner charging performance. Since significant changes in either $\boldsymbol{q/m}$ or toner concentration can markedly alter the shape of the output tone reproduction curve (e.g., by reducing the number of output halftone densities), complex control strategies must be devised to accommodate fluctuations in toner/developer performance. In theory, compensatory changes can be made to other non-toner factors that affect xerographic development (e.g., development potential via changes in either the development bias or the intensity of the scanning laser beam), but in practice total system latitude considerations limit the degree to which any factor can be manipulated.[32] For full-color xerographic imaging, halftone rendition problems are especially troublesome, since four separate tone reproduction curves must be maintained simultaneously. As a result, for present technologies, stable xerographic halftone imaging requires frequent in-machine measurements on calibration target images, with complex feedback algorithms being used to apply corrections to key control factors.[33] (Again, this aspect of xerographic digital imaging is quite different from offset lithography — in the latter technology, on-line calibration is not normally applied during a print run; rather, following iterative pre-press adjustments, the press operates in a stable equilibrated condition since the print run involves repeated identical impressions.[34])

As should be clear from the topics discussed thus far, the transition from analog to digital imaging has greatly expanded the capabilities of xerography, especially in the area of full-color, pictorial printing. However, it should also be clear that this new mode of imaging has imposed an increased standard of performance on xerographic imaging materials, especially with respect to stability. In particular, toner robustness (in both the materials and performance sense) appears to be a key enabler, and eventual technological breakthroughs in this area will be most beneficial.

In the short-term, however, inventive xerographic process technologists will likely propose new marking technologies aimed at circumventing the presently perceived deficiencies in marking materials. New methods for toner charging and transport without the use of development brushes or donor rolls might seem to be a promising route towards robustness achieved via simplification. However, if past experience is a reliable guide, it is likely that elegantly simple xerographic marking subsystems will in fact be enabled only via increasingly complex toner designs. From a toner/carrier viewpoint, therefore, a worthwhile goal for marking process technologists might be the development of imaging subsystems that deliver outstanding performance from simple, robust toner designs.

Finally, though the ability to copy on "plain" paper was a key feature of original analog-era copiers, the ability of substrates to enhance output copy quality represents yet another opportunity for improvements in digital xerography. Specialized printing papers and post- printing surface treatments are important features in high quality offset lithography,[35] and the recent development of "photoquality" ink jet printing is another area in which specialized substrates have provided increased image quality.[36] In the area of digital xerography, the Fuji Xerox Photo Recipe product,[37] which uses resin-coated paper to add nearphotographic quality to xerographic images, is a present-day demonstration of the improvements that can be gained from a "smart" substrate. Clearly, quality-enabling substrate/toner interactions represent yet another new R&D area created by the transition from analog to digital xerography.[38,39]

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Biography

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