A Dot-gain Analysis of Inkjet Printing

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Abstract

The objective of this research is to investigate the mechanisms that cause dot gain on inkjet papers. In addition, this research examines whether there is an explicit relationship between a paper property and the dot gain. Experiments were first conducted to generate YMCK color bars on both inkjet and non-inkjet papers. Optical density was then measured using a spectrodensitometer. Values of dot gain were subsequently calculated and analyzed based on the Murray-Davies equation and the Yule-Nielsen's photon modification. The results indicate that for inkjet papers, the photon spreading is the major mechanism that causes dot gain, and the magnitude of ink-particle spreading is nearly negligible. On the other hand, for non-inkjet papers, both photon and ink-particle spreadings are significant mechanisms for the dot gain, with the ink-particle spreading being more effective than the photon spreading. In addition, it can be concluded from this work that among various paper properties being tested, only ink absorptivity yields a mathematical, functional correlation with the values of dot gain. Other properties such as porosity and smoothness do not produce a one-to-one relationship against the dot gain. Finally, experimental data reveal that the maximum dot gain occurs at around 40% tint, regardless of the type of paper samples. And inkjet papers always produce less dot gain than non-inkjet papers.

Introduction

While optoelectronic technology, genetic technology, and nanotechnology are sprouting to become the key sciences for the 21st century, the development of digital printing is also becoming dynamic. The application of digital printing is all around us. Take color photocopiers, color facsimiles, and laser and inkjet printers. These electronic duplicators use fine chemicals and complex processes to produce images and/or written material on specialty papers. The term digital printing was dubbed because the printing process is controlled directly by the computer and has a couple of synonyms, i.e., non-impact printing (NIP) and electronic printing. Commercially, the world market of digital printing is growing strongly and may have a volume of a billion Swiss francs by the year 2005, estimated just for the inks and toners.[1]

To accomplish the job of image duplication, digital printing technology combines four systems into one integrated production process. These four systems are: the computer, the printing engine, the inks, and the ink-accepting substrates that are generally a sheet of paper. Although all four systems are critical to yield caliber print images, one single parameter is always being used in the technology to evaluate the print quality, i.e., the dot area. Dot area in halftone applications has the dimension of ink area per unit printing area, and its unit is percent (%). Dot area can numerically evaluate the print quality because if the dot area of the print is greater than that of the preset computer value, then the inks must have spread (diffused) over the surface of the paper. The ink-spreading condition, which is also called the dot-gain phenomenon, can adversely affect the print quality, inasmuch as the occurrence of dot gain implies that different color inks are overlapped with each other, resulting in color misrepresentation and in loss of image details (the sharpness). Thus, an increased dot-gain value means a decreased print quality.

Mechanistically, the occurrence of dot gain is the result of both the physical dot gain and the optical dot gain. The physical dot gain refers to the surface forces acting on the colloidal ink particles, causing them to spread radially on the paper surface plane. And the optical dot gain implies the scattering behavior of photons between the ink layer and paper surface, creating a corona effect around an ink dot. Experimentally, specific numerical values of the dot gain can be determined using a spectrodensitometer and two equations, namely, the Murray-Davies equation and the Yule-Nielsen equation.[2, 3] Murray-Davies equation takes the form of

$$a = 100 \times [1 - 10^{(Dp - Dt)}] / [1 - 10^{(Dp - Ds)}] \qquad (1)$$

where a is the dot area, D_p is the (optical) density of paper, D_t is the density of a tint, and D_s is the density of the solid (100% tint). And the Yule-Nielsen equation is expressed as

$$a = 100 \times [1 - 10^{(Dp - Dt)/n}] / [1 - 10^{(Dp - Ds)/n}] \qquad (2)$$

where all parameters are the same as in Equation (1), except the factor n. This photon factor (n) is used to quantitatively separate the optical dot gain from the physical dot gain. Thus, one can compare the two mechanisms.

The objective of this research is to investigate the mechanisms that cause dot gain. In addition, this research examines whether there is an explicit (mathematical) pattern between a paper property and dot gain.

Experimental

Phase I–Paper Testing

Four different types of paper were first collected and grouped into nine samples. The paper types are newsprint, Xerox, poster, and inkjet. The sample names and symbols are organized in Table I. There are two commercial newsprint papers used for paper testing. For inkjet papers, the first two kinds are Epson Photoquality Glossy Paper and Epson Stylus Color Inkjet Paper for 720 dpi Printing respectively, and the third kind was supplied by a commercial manufacturing company. Those paper samples that were not separated into the felt and wire sides were tested on the coated surfaces when the paper two-sidedness was considered as a differentia.

Table I. Paper Sample Names and Symbols.

Sample name	Sample symbol
Newsprint-1-felt side	NPC-F
Newsprint-1-wire side	NPC-W
Newsprint-2-felt side	NPT-F
Newsprint-2-wire side	NPT-W
Xerox copy paper	Xero
Poster paper	PT
Ink-jet paper-1	IJ1
Ink-jet paper-2	IJ2
Ink-jet paper-3	IJ3

Four classes of paper properties, i.e., structural, surface, optical and adhesive, were measured on all nine paper samples. All data reported are averages of at least five repeated measurements. For the structural properties, basis weight, thickness, density and porosity were tested. For the surface properties, only smoothness was measured. For the optical properties, quantities of opacity, brightness and gloss were recorded. And finally, for the adhesive property, ink absorptivity was determined. Except ink absorptivity, all measured data were obtained following the published procedures of TAPPI TEST METHODS and the ink absorptivity was measured using the K & N procedures of ink absorptivity with D96 ink.

Phase II–Inking and Dot Gain Determination

The inking process was accomplished using an Epson Stylus 850 inkjet printer interfaced to a Macintosh G3 computer. Individual CMYK color patches (bars) for all nine paper samples in 5% dot-area increment were created using Adobe Photoshop 5.0 program. The software parameter setup was kept constant throughout the whole inking experiments with “plain paper” selected in the software. The optical density of all color patches and blank papers was determined by an X-rite 528 multi-function spectrodensitometer. Apparent dot area (%) was then calculated using the Murray-Davies equation. Data of the dot gain were next computed by subtracting a specific tint value from the apparent dot area. The photon factor (n) were lastly determined following the trial-and-error method described by Yule-Nielsen.[3]

Results and Discussion

Dot Gain and Tint

Figure 1 depicts that when magenta ink is applied to the color patches on all paper samples, the highest dot gain occurs at 40% tint regardless of the paper types. Moreover, the inkjet (IJ) papers consistently yield less dot gain than non-inkjet (NIJ) papers, with a maximum being about 27% as oppose to approximately 44% for the NIJ papers. This implies that the surface characteristics of IJ papers are superior in the sense of providing less dot gain than that of NIJ papers. However, as occurred with NIJ papers, dot gain peaks at around 40% tint for IJ papers as well.

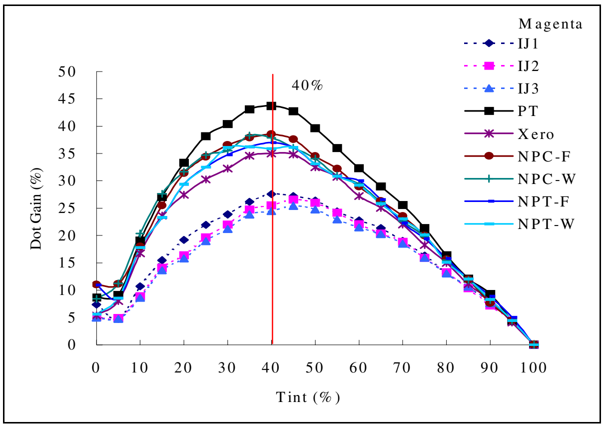

Figure 1. Dot gain versus tint value of all paper samples with magenta ink

The roughly parabolic symmetry in Figure 1 is perhaps a compounded result of both the physical and optical dot gains. It is plausible that when the tint is at lower extent (from 0% and up), the physical dot gain dominates the process of dot spreading, therefore as the tint increases dot gain increases. On the other hand, when the tint is at higher extent (from 100% and down), the optical dot gain precedes the physical one and becomes the major pathway for dot augmentation. Nonetheless, the physical mechanism would reach a maximum as the tint increases to a certain magnitude, possibly due to shrinkage and/or a strengthened internal bonding among the mass of the ink particles. But for the optical mechanism, as the tint increases dot gain diminishes because there would be less non-image area for the optical effect (photon scattering) to take place. Combining these events together, the maxima of the two mechanisms could coincide and afford a peak value for the dot gain, as exemplified in Figure 1.

As for other types of ink, including cyan, yellow, black and mixture of CMYK inks, they all produced the similar parabolic pattern of results as shown in Figure 1 where only magenta ink is considered.[4]

Relationship between Dot Gain and Paper Properties

Among all the paper properties tested for finding a regular pattern with the dot gain, only ink absorptivity successfully produced a mathematical, functional relationship with the dot gain. However, this relationship is opposite in proportionate direction for IJ and NIJ samples. As shown in Figure 2 that dot gain increases along with the ink absorptivity for IJ papers, but it decreases for NIJ papers.

This outcome suggests that governing mechanisms of dot gain are not the same for different paper samples, i.e., between IJ and NIJ samples. As will be proved later (see Figures 8 and 9) that dot gain is caused only by the photon effect for the inkjet papers, but is caused by both the physical and optical mechanisms for the non-inkjet papers. Thus, the result in Figure 2 implies that the more ink absorbed on the NIJ paper surface would decrease the magnitude of the physical dot gain, possibly due to a strengthened internal bonding among the ink particles. Yet on the other hand, Figure 2 also implies that when more ink particles are on the surface of the IJ papers, more photon scattering occurs resulting in increased dot gain. Notice also that NIJ papers always generate more dot gain than IJ papers, since their surfaces are not deliberately formulated for receipting inks of inkjet printers.

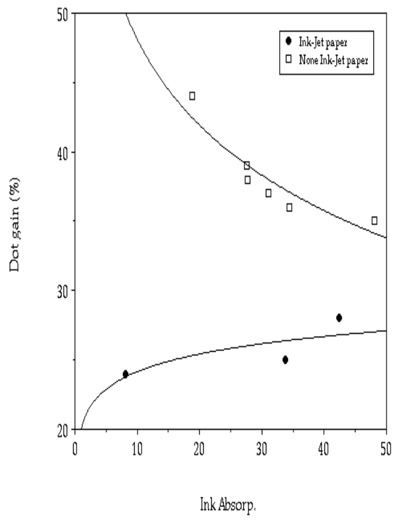

Figure 2. Dot gain versus ink absorptivity

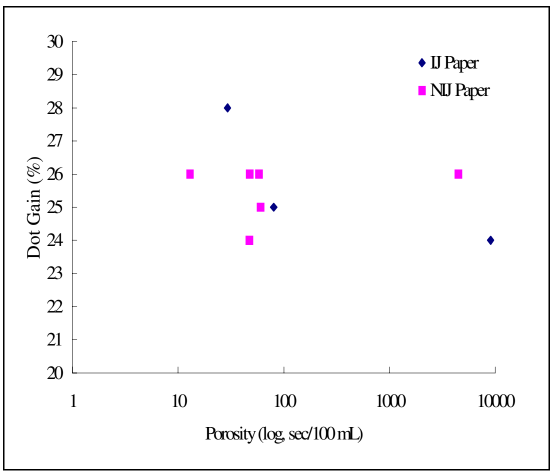

Figure 3. Dot gain versus paper porosity

Figures 3 and 4 are examples illustrating that paper properties other than ink absorptivity could not produce smooth, functionally one-to-one curves between dot gain and the properties. Figure 3 is the result of paper porosity, and Figure 4 is of paper brightness.

Although from engineering, the porosity should provide an influence on the amount of ink absorption, which in turn could affect the extent of dot gain, Figure 3 does not explicate this clearly. This can mean that the magnitude of dot gain is governed by multiple factors occurring at the same time. And when all these factors are happening collectively and simultaneously, ink absorptivity turns out to be the one factor that can produce a smooth, mathematical relationship with the dot gain, and not other properties. The finding suggests that for practical purposes, ink absorptivity has the advantage over other properties for predicting the quality (dot gain) of a final print.

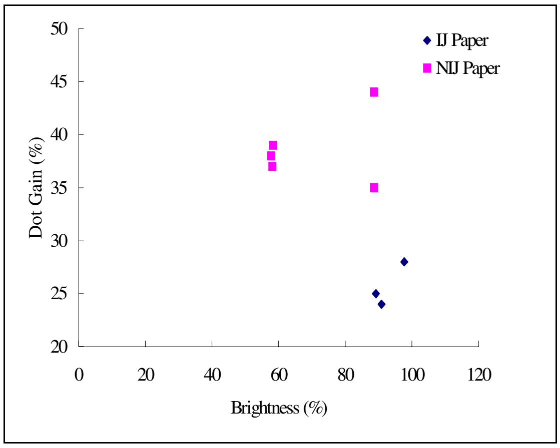

Figure 4. Dot gain versus paper brightness

The Photon Factor

Figure 5 depicts visualization on the phenomenon of dot gain. As can be seen that when the tint is set at a fixed value (40%), the ink dots spread significantly broader on the non-inkjet paper surface (below) than inkjet surface (above). The dot area is approximately 4 times less on the inkjet surface than on the non-inkjet surface.

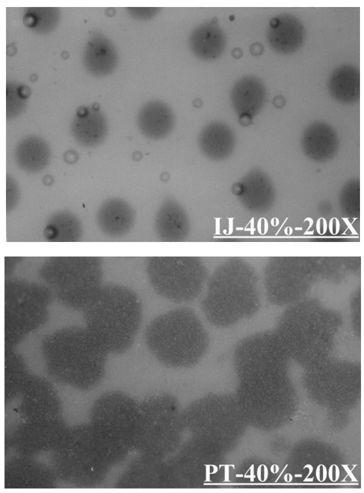

Figure 5. The dot gain phenomenon visualized

Both the physical surface forces acting on the ink particles and the scattering behavior of photons cause the ink dot spreading. To individually calculate these two contributing mechanisms, the photon factor (n) in the Yule-Nielsen's equation, see equation (2), is used to remove the photon contribution from total dot gain obtained from the Murray-Davies equation (equation 1). The photon factor can be determined using a trial-and-error method that corrects a predicted (or called integrated) optical density of a specific tint back to the experimentally measured value. Figure 6 takes magenta ink as an example to show that when n = 100 the integrated densities at different dot areas (tint) coincide with the ideal (experimentally measured) data. The n = 100 was first determined using a particular tint value of 40%, and then it was substituted for various other tint values.

The physical meaning of the n can be viewed as the capacity of the photons to cause optical dot gain. The higher the value n, the more optical dot gain will be resulted from the scattering behavior of photons. Figure 7 demonstrates a proof for the photon capacity on optical dot gain. Notice, however, that optical dot gain reaches saturation as n increases, implying that a specific number can approximate the photon activity. This fact of saturation also suggests that photon (corona) effect is limited by the ink-paper interface system.

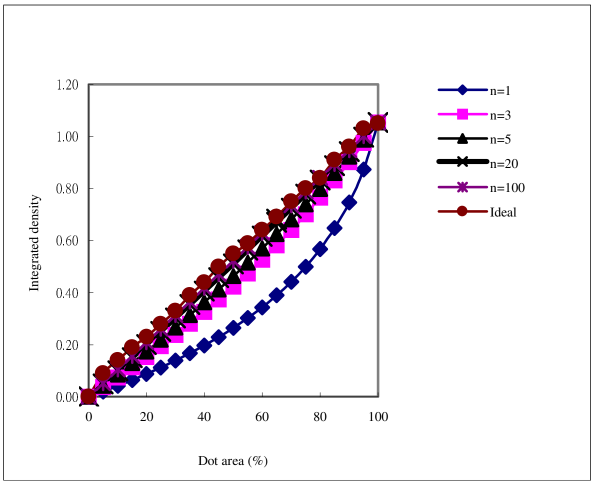

Figure 6. Determination of n by a trial-and-error method

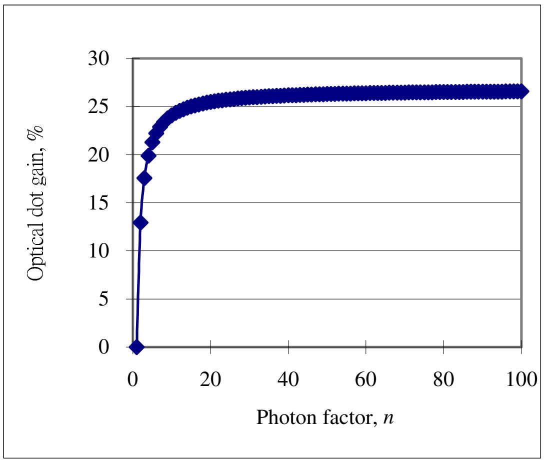

Figure 7. Optical dot gain increases as n increases, but saturates after a certain value of n.

Partial Contributions from the Optical and Physical Dot Gain

After separating the optical dot gain from the physical dot gain, their individual contributions to the total dot gain can be plotted and compared. Figure 8 explicitly delineates that for inkjet papers with magenta ink, the optical dot gain is almost the only mechanism that causes dot gain on paper surface. This is probably because the coating formulation involving silica pigments produces a directed force by which the ink particles would penetrate only vertically into the paper surface. And at the same time, the silica formulation can even repel the planar radial movement of the ink particles, causing shrinkage on the dot area. This can be deduced from the fact that negative dot gains were found for the physical effect in Figure 8.

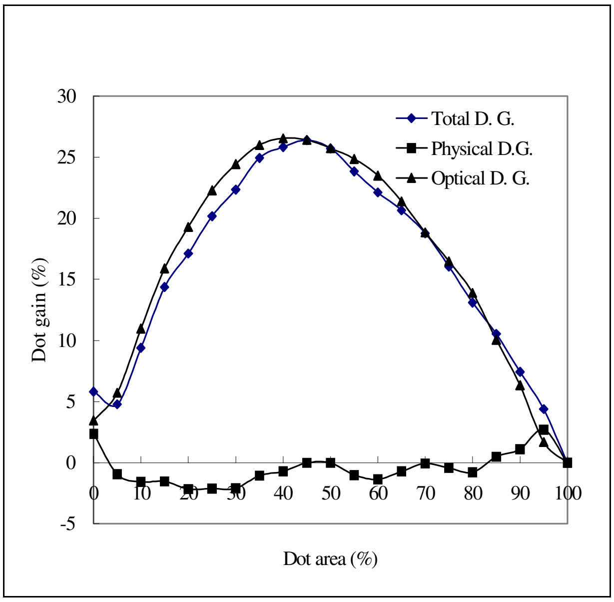

Figure 8. Partial contributions from optical and physical dot gains for an inkjet paper with magenta ink

However, when analyzing partial contributions for the non-inkjet papers with the same trial-and-error method, the results are in stark contrast with that of inkjet papers. Figure 9 reveals that both optical and physical dot gains are significant mechanisms for the final, total dot gain. This outcome has to do with the surface characteristics of non-inkjet papers that are distinctly different than inkjet papers with respect to the interactions between ink particles and paper surface. The fact that the physical dot gain is roughly always contributing more to the total dot gain than the optical dot gain should be due to the surface forces which pull ink particles outward in the planar radial directions. These pulls in addition to the optical effect ultimately result in an enhanced dot gain phenomenon with non-inkjet papers (see Figures 1, 2 and 5). Notice also that the greatest dot gains always occur around 40%-50% tint; regardless the samples are inkjet or non-inkjet. As explained previously, around 40% tint is where optical dot gain and physical dot gain achieve their maxima.

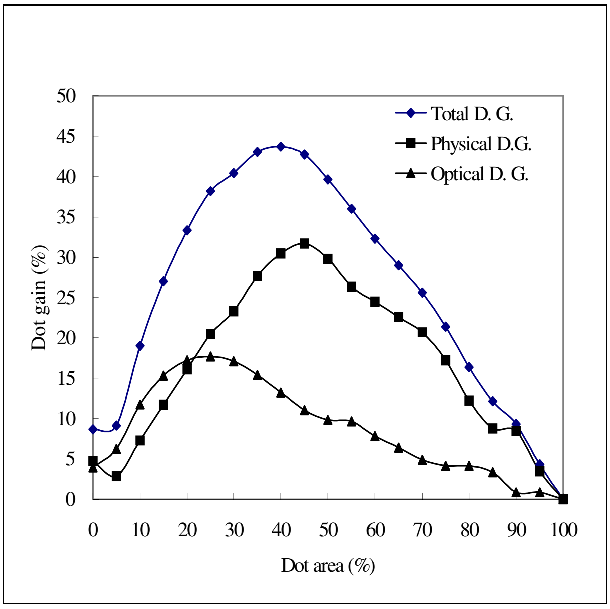

Figure 9. Partial contributions from optical and physical dot gains for a non-inkjet paper with magenta ink

Thus, the major mechanism for dot gain of inkjet papers is the photon scattering behavior. And future research should be focused into this area to find a solution that can minimize the optical dot gain. Consequently, a maximized image resolution could be achieved because of this image refining solution for inkjet papers.

Conclusion

The highest dot gain occurs at around 40% tint for both inkjet and non-inkjet papers, and for all ink types. This is probably due to a maximizing feat of the physical and optical dot gains at this particular tint. Moreover, inkjet papers consistently produce considerably less dot gain than non-inkjet papers, inasmuch as it has a special coating formulation that leads to only vertical penetration of the ink particles. Furthermore, among the paper properties tested, only ink absorptivity displays a functional relationship against dot gain, implying that ink absorptivity has the advantage over other properties for predicting print quality. Finally, photon effect is the major mechanism for dot gain with inkjet papers. Consequently, how we invent a solution to minimize this photon effect should be a focus for subsequent research.

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Biography

Shen-yu Chang is currently an associate professor in the Department of Chemical Engineering, Chinese Culture University, Taiwan. He received his Ph.D. in Paper Science and Engineering from the State University of New York in 1993. He worked in ink formulation for BOPP films and since 1994 he has been teaching and researching in chemical engineering and paper engineering. His recent interests include digital printing technologies, novel papermaking methods, and mathematical modeling of print-related phenomena. He is a member of IS&T, AIChE, TAPPI and Appita.