# Characterizing and Modeling Coalescence in Inkjet Printing

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## Abstract

In liquid inkjet printing, a critical quality issue is the coalescence of ink on the media surface. This paper describes a technique for quantifying coalescence using an automated print quality analysis system. This technique measures spatial variability of reflectance caused by coalescence. Uniformity is compared in test samples printed with different printing technologies. The technique was used to study the effects of different media coatings on the magnitude of coalescence in inkjet printing. The roles of the surface tension of the ink, the surface energy of the media and the rate of ink absorption by the media are examined for insight into the mechanisms of coalescence.[1]

## Introduction

Much time and effort have been invested in developing printing algorithms capable of producing excellent print quality in inkjet printing.[2,3,4] Many factors operating in concert influence the ultimate quality of the print. For example, ink-media interactions and interactions between inkjet drops play a critical role. If these interactions are not well controlled, poor print quality characteristics such as bleed, feathering, and coalescence can result.

This paper describes a quantification method for characterizing coalescence with an automated print quality measurement system. This method shows that the spatial variability of reflectances in a solid fill area is an important factor for quantifying coalescence. The role that media and ink play in the phenomenon of coalescence and the underlying mechanisms are also examined.

## Experimental Approach

### Sample Preparation

Test samples were prepared by applying a thin topcoat of polymer on a photobase paper already coated with an absorbent intercoat. Three different sample types (here designated Surface A, Surface B, and Surface C) were created using different polymer topcoats. Test patterns were then printed on the samples using a Canon BJC-4300 Bubble Jet™ inkjet printer and the OEM ink set. The test patterns consisted of red, green, blue, cyan, magenta, yellow, and black solid fill areas.

For purposes of comparison, print samples were also produced using an HP Color LaserJet 5 laser printer and a Fujix Pictro[5] printer. The printers selected are generally found to produce good uniformity. The Fujix printer, which uses a silver halide photographic process with laser diode exposure, was chosen as a reference in this study for its excellent uniformity in solid fills.

### Measurements and Calculations

All coalescence measurements were made using a QEA IAS-1000™ Automated Print Quality Analysis System. All surface tension and contact angle measurements were made using a First Ten Angstroms® Dynamic Contact Angle System. Coalescence calculations are detailed below.

## Results

### Coalescence Quantification

Although there are many different aspects of print quality, the quality of large areas of solid fill is often of particular interest, especially in "business graphics." These tend to contain a number of large areas filled with solid colors, as in pie charts. While color accuracy can be important in business graphics applications, color uniformity is typically more important than color accuracy. (This contrasts with digital photos, where color accuracy is very important. However, because photos are less likely to have solid fill areas, uniformity is less of a problem.)

Non-uniformity in solid fill areas can have many causes. In inkjet printers, fine banding (one type of non-uniformity) is frequently caused by missing or poorly aligned jets. Bleeding, feathering and coalescence, as noted, are other important contributors. To begin to understand the mechanisms that produce non-uniformity in prints, a necessary starting point is to select an appropriate measure, or *metric*, of uniformity.

Although there are many uniformity metrics available,[6] it is preferable to work with an internationally recognized standard. The ISO-13660 draft standard, for example, prescribes methods for measuring *graininess* and *mottle*, which are metrics of “micro uniformity” and “macro uniformity,” respectively.[7] Figure 1 shows the proposed ISO method schematically. A digital image of the print area to be examined is acquired, typically by a digital camera or scanner. The region of interest (ROI) is subdivided into one hundred smaller regions called tiles. The ROI prescribed by the ISO draft standard is 12.7 × 12.7 mm and the tiles are 1.27 × 1.27 mm. Each tile within the ROI is 30 × 30 pixels. Within each tile, the average optical density, $m_i$, and standard deviation of the optical density, $\sigma_i$, are calculated. From this data, the mottle can be calculated as the standard deviations (stdev) of $m_i$, and the graininess by the equation in Figure 1.

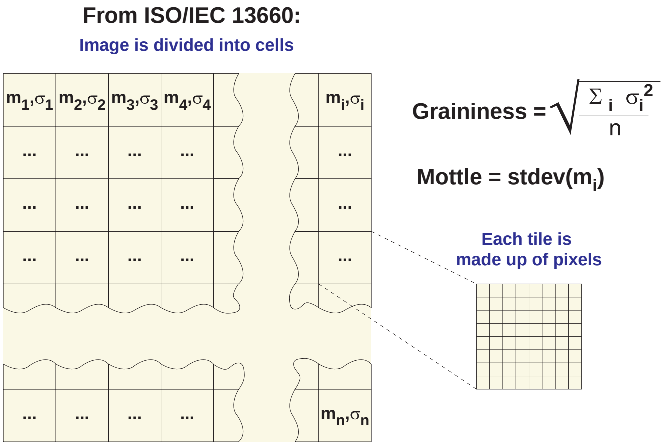


*Figure 1. Image area is divided into a number of tiles for calculating graininess and mottle.*

## Mottle and Spatial Frequency

Mottle as defined above was initially chosen as the measure of coalescence for this study because in principle it is designed to exclude high frequency variations in image density associated with halftoning and reveal the kinds of low frequency variations caused by coalescence. However, we recognized early on that ISO 13660 has limitations that make it inappropriate for analyzing mottle due to coalescence. First, ISO 13660 is intended for monochrome printing and for that reason uses optical density (OD) in all its measurements. Because of the logarithmic relationship between OD and the amount of light reflected from a surface, the use of OD in metrics of non-uniformity is not suitable for analyzing the broad range of reflectance levels in color prints. Second, ISO 13660 uses a fixed tile size to distinguish mottle from graininess, introducing an artificial cut-off that has not been fully tested, particularly for color prints.

In view of these limitations, we decided not to apply the ISO method as is, but to use a variant with some important differences. The two most significant differences are 1) the use of simple Gray Scale Values (GSV) — numbers between 0 and 255 — as the unit of reflectance and 2) the use of a variable tile size. The GSV, in contrast to optical density, provides a linear scale for measuring reflectance, and the variable tile size takes into account the dependency of mottle measurements on spatial frequency. This second point is extremely critical in view of the fact that human perception of reflectance variations is also very sensitive to the scale of the non-uniformity.

In a typical measurement in our study, we obtained the mottle value for a captured field of view using the computational approach outlined in Figure 1. The measured mottle is given as M $_{t\ \mu m}$, where M stands for mottle and *t* is the tile size. M $_{500\ \mu m}$, for example, is mottle measured with a tile size of 500 µm. When interpreting mottle data, larger values indicate more non-uniformity and smaller values indicate less non-uniformity.

Figure 2 shows mottle measurements taken at a range of tile sizes on areas printed with solid magenta. The data show that all five of the test samples have virtually identical mottle values at the ISO-specified cut-off frequency corresponding to a tile size of 1270 µm. Despite the very visible coalescence in some of these samples, the ISO method could not detect the differences. On the other hand, by using variable tile sizes, distinct differences in mottle among the five samples become apparent, particularly at smaller tile sizes. Figure 3 shows images of the five samples; the correspondence of these images to the numerical results in Figure 2 is clear. From Figures 2 and 3, several observations can be made. First, mottle is lowest for the Fujix Pictro, consistent with visual observation of the samples. Second, for the Color LaserJet 5, mottle is relatively low at tile sizes above 160 µm, while below 160 µm measured mottle rises sharply. However, this sample, shown in Figure 3b, appears quite uniform to the observer. We speculate, therefore, that 160 µm is probably at the lower limit of perceptibility. Third, the three inkjet samples show clear differences, Surface A showing more mottle than

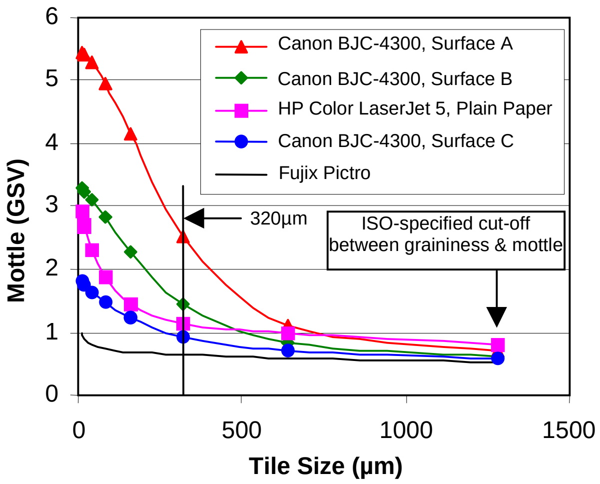
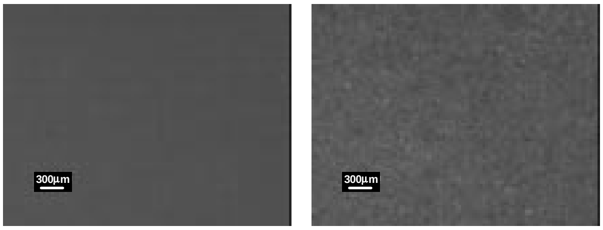
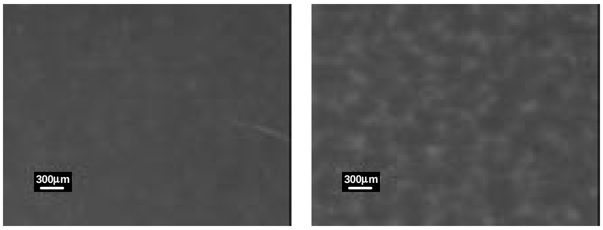


*Figure 2. Mottle of magenta solid fill areas*

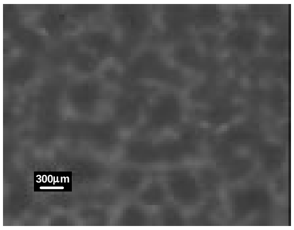
Surface B, and Surface B showing more mottle than Surface C. In fact, Surface C shows even less mottle than output from the Color LaserJet 5. Surfaces A and B are both decidedly non-uniform, as can be seen in Figure 3.



*a. Fujix Pictro* *b. HP LaserJet 5*



*c. Canon BJC 4300 Surface C* *d. Canon BJC 4300 Surface B*



*e. Canon BJC-4300 Surface A*

*Figure 3. Magnified magenta solid fills (contrast has been adjusted for illustrative purposes).*

Figures 2 and 3 show results for solid magenta only, but the same measurements were also made for the other primary and secondary colors. In every case, the results were similar to those for magenta. However, the blue and red solid fill areas tended to show very little measurable difference between the print samples until the cell size got below 300 µm.

After experimenting with different tile sizes and observing how our quantitative results correlated with perceptible non-uniformity in the test samples, we decided on a tile size of 320 µm. This is above the lower limit of perceptibility derived for the Color LaserJet 5 sample. Comparing the mottle values at various tile sizes in Figure 2 with the magnified samples in Figure 3, it is apparent that the selected frequency exposes meaningful differences in uniformity. Greater mottle values can be observed at smaller tile sizes, but this has little practical value since at these frequencies differences become imperceptible to the unaided eye.

## Mottle Measurements for Different Colors

An important consideration in making mottle measurements on color prints is how to treat different colors. For example, can a mottle value of 1.2 on a cyan printed area be compared with a mottle value of 1.2 on a yellow printed area? Consider, as examples, the mottle data for the Fujix printer samples and the Canon inkjet Surface B sample, shown in Figure 4. The data clearly indicate that overall the inkjet sample has greater non-uniformity than the Fujix sample. However, when the individual colors are examined, there are some surprises. Most notably, the data suggest that areas of yellow and white, the two lightest colors, on both samples have very large non-uniformity. What are the implications of this observation?

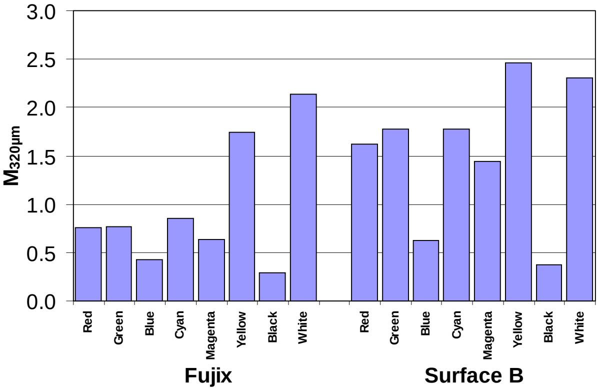


*Figure 4. Mottle data for Fujix and Surface B samples*

To explore the relationship between measured mottle and the lightness of a colored area, a cross-plot was created, as shown in Figure 5. This data, based on the Fujix print sample, shows a clear linear relationship between mottle and average reflectance values. The same trend was observed in the mottle results of the analysis of samples from the HP Color LaserJet. This suggests that something fundamental is at work here. In terms of mottle, the correlation suggests that lighter colors will typically have more variation and larger mottle values than darker colors and that direct comparisons of mottle values from areas with different colors may not be meaningful.

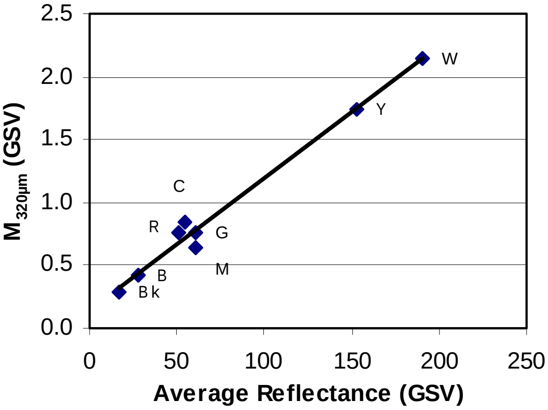


*Figure 5. Mottle data for Fujix printer sample for red(R), green(G), blue(B), cyan(C), magenta(M), yellow(Y), black(Bk), and white(W) solid fill areas.*

A key to analyzing or comparing mottle data obtained on samples of different colors can be gleaned from Figure 5. Because of the linear relationship shown, we decided to divide the mottle values by their respective average reflectance values, thereby obtaining normalized mottle values. The data in Figure 4 are shown normalized in Figure 6.

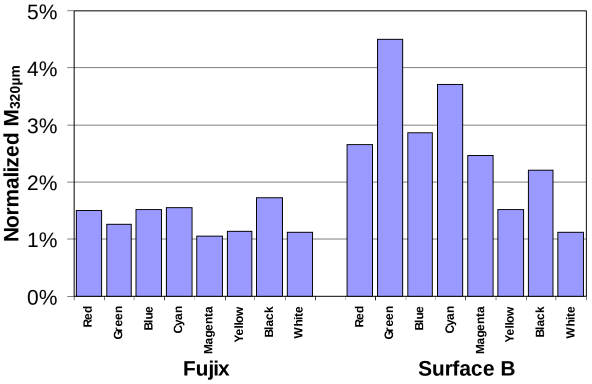


*Figure 6. Normalized mottle data for Fujix and Surface B samples*

The results of normalization are quite dramatic. Almost all color patches on the Fujix sample show consistently low values of normalized mottle, suggesting that normalized mottle may be a useful “color-independent” measure of non-uniformity. The inkjet sample shows significant variations in normalized mottle among the different colors, with green and cyan exhibiting the worst mottle. Using the Fujix data as a benchmark, a clear goal can be developed for acceptable coalescence in inkjet printing. If the normalized mottle for the inkjet samples could be reduced to about 1.4%, we would expect the printed images to look as uniform as the Fujix samples. An important point here is that separate uniformity goals need not be set for each color; normalizing the mottle data eliminates that need.

It should be pointed out that subtle issues appear to be involved in the normalized mottle analysis. For example, the simple normalization scheme makes black areas numerically worse (larger). This is an artifact of the fact that the line in Figure 5 does not pass through the origin, possibly a consequence of inherent noise in the measurement system.

In the next section, we will apply the normalized mottle idea in investigating the physical basis of ink coalescence. To do this we will look at the interaction between the Canon inks and inkjet media. Figure 6 clearly shows that the color of the ink has a noticeable effect on the magnitude of coalescence. This suggests that ink chemistry plays an important role in the phenomenon of coalescence. For simplicity, we will restrict our study to magenta ink. The choice of magenta is somewhat arbitrary. Figure 7 shows the normalized mottle data for the magenta areas of the five samples. This set of data will be examined in more detail in the next section.

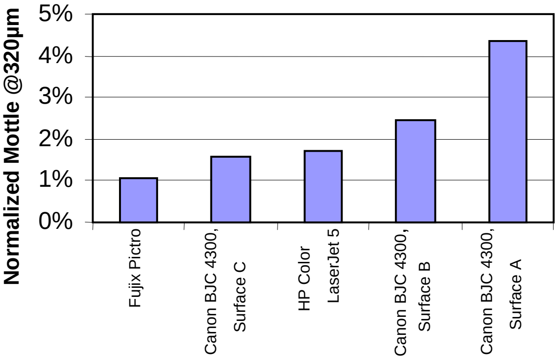


*Figure 7. Normalized magenta mottle measurements.*

## Coalescence Model

To predict, and hence control, coalescence in inkjet ink-media combinations, an understanding of the underlying mechanisms must be developed. We start with the hypothesis that coalescence is affected by the surface tension of the ink, the surface energy of the media, and the rate of drop stabilization in the media surface.

The surface tension of the inkjet ink and surface energy of the media play complementary roles in coalescence. A certain amount of spreading of the ink droplets is needed for complete, uniform fill. On the other hand, excess spreading may allow too much drop-to-drop interaction and cause dye to migrate from the point of application. Ink spreading can be controlled both by adjusting the surface tension of the ink and by adjusting the surface energy of the media.

To observe ink-media interactions, contact angle measurements were made on the Surface A, B and C inkjet media. The measurement instrument used allows measurements to be made in rapid succession so the rate of change can be observed. Figure 8 shows data for drops of magenta ink. This ink had a measured surface tension of 31.7 dyne/cm. The graph shows the contact angle immediately after the ink is applied to the surface and the contact angle has stabilized. The difference between the initial and final contact angles is also shown.

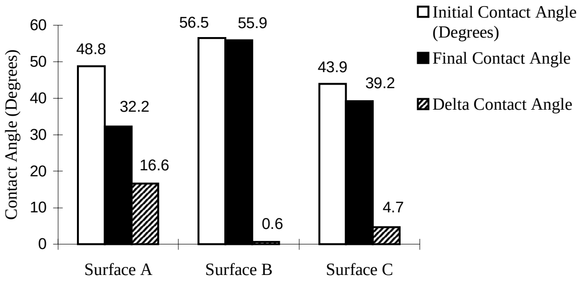


*Figure 8. Contact angle data for magenta ink*

An interesting phenomenon noted during this study was the rate at which drops applied to each surface reached their final observed contact angle, as shown in Figure 9. Surface A took a significantly longer time to reach its final contact angle than did either Surface C or B. Unfortunately, with the small difference between the initial and final contact angle, a rate was difficult to determine for Surface B.

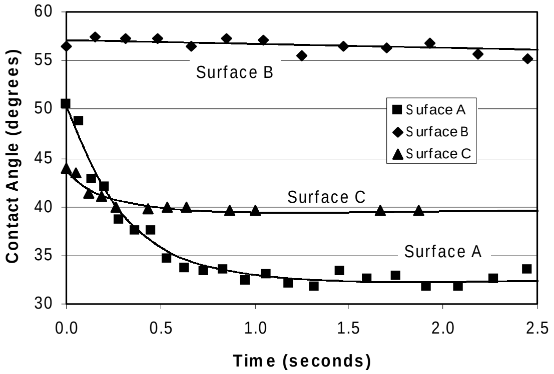


*Figure 9. Stabilization of contact angle with time.*

Figure 10 shows drop stabilization time compared to $M_{320\mu m}$. This graph suggests that the rate of drop stabilization has an effect on coalescence, with slower rates of stabilization leading to higher coalescence. The slower stabilization rate may allow the dye in the ink drops more time to migrate from the initial point of application. Figure 10 also suggests that the rate of drop stabilization alone is not the only controlling factor in coalescence. For example, while the stabilization time is less for Surface B than for Surface C, Surface B mottle is higher than Surface C mottle. Further investigation is needed to clarify the mechanisms that account for this.

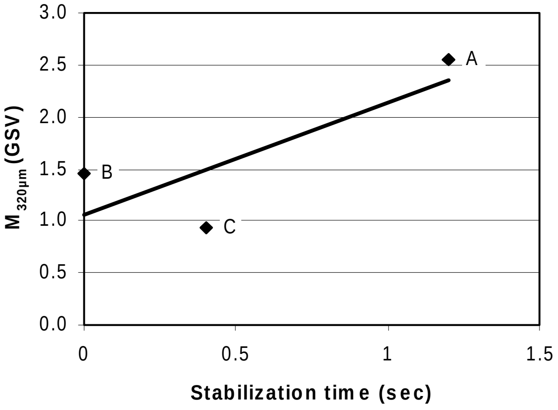


*Figure 10. Cross plot of mottle and stabilization time.*

## Discussion

A quantitative image non-uniformity metric using variable tile sizes is developed to measure mottle produced by coalescence of inkjet ink on paper. Mottle measurements on several inkjet papers are compared with measurements on laser prints and digital silver halide prints. The mottle metric is shown to provide critical information about the spatial content of non-uniformity and how this differs among different printing technologies. Furthermore, it is found that mottle can be "normalized" to compensate for the effect of color differences, effectively creating a measure of uniformity that is color independent.

This paper shows the dramatic effect of different media coatings on coalescence. The phenomenon of coalescence is complex. The data reported here point to the importance of the rate of drop stabilization. This stabilization may occur because of surface tension and surface energy effects or it may occur because of the rate at which the drop is absorbed into the coating. Further work should focus on acquiring data using drops approximately the size of actual commercial inkjet drops (rather than the relatively large drops used in this study.) Drop volume data versus time and contact angle data versus time should also be collected.

## Conclusions

The following can be summarized from this paper:

1) A metric of non-uniformity, called mottle, is developed.
2) Mottle is defined in such a way that the spatial frequency content of a non-uniformly filled area can be examined.
3) Mottle can be normalized in such a way that the non-uniformity of areas of different color fill can be directly compared.
4) The mottle metric is applied to the problem of inkjet coalescence.
5) The magnitude of coalescence is found to be related to the rate of stabilization of the contact angle of ink drops.

## Acknowledgments

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## Biography

Nathan Jones has been employed by Arkwright for two years. His primary work involves development and commercialization of new inkjet media. He has a B.S. in chemistry from Cal Poly San Luis Obispo and an M.S. in polymer Science and Engineering from the University of Massachusetts at Amherst.