Print Quality Considerations in Ink Jet Printing in Industrial Applications

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Abstract

The print quality of text or graphics becomes of primary importance as digital printing applications on packaging shift from plain date coding to ingredient, promotional or other type of text information and logos. In our laboratory, we have investigated the print quality of various continuous and "drop on demand" ink jet printers on a number of substrates. In this paper, we present our work on ink media interactions and their effect on print quality metrics such as print density, sharpness, etc. In industrial applications, end use constraints as well as print head limitations narrow the latitude of ink selection. As media availability may also be limited, process conditions such as preheating or post drying become important to assure fast drying and good print quality. For example, a 300 dpi DOD system with a pigment-based ink gave excellent print quality (comparable to gravure) but required preheating in order to dry in less than 10 seconds.

Introduction

Ink jet systems with industrial applications such as date coding, bar coding and low end text and graphics printing have become an integral part of industrial processes. Because of the speeds involved and the nature of industrial environments, continuous ink jet systems became the preferred technology for industrial applications.[1] These systems are limited, however, in print resolution, ink formulation latitude and reliability when not operated continuously. On the other hand, DOD systems offer wider ink latitude and resolution but come short on speed as they usually operate at 4-8 kHz.

At the other end of the spectrum, high-end "drop on demand" systems for Small Office- Home Office applications have been enjoying a tremendous success. This occurred as advances in print head technologies progressed with developments in ink formulations and media designs. As technologies for office or home applications are entering a mature cycle, applications for industrial markets are also being explored for the high resolution print systems.

Industrial applications can be grouped in categories depending on the industrial product itself or the general functionality of the product being printed.[2] For instance, we may distinguish between food or tobacco applications for ink jet printing or we may consider both applications under the broader umbrella of industrial packaging. It must be emphasized that each industrial application is unique, and the requirements imposed on digital printing by the primary industrial process or product end use usually dictate which printing technology is most likely to be successfully implemented.

Printing in industrial applications can be on line or near/off line. The lay out of the process, the industrial environment and, of course, economics, determine which option to select. Philip Morris USA has been exploring the application of printing variable information on primary packaging on or near line.[3] The requirements for a system that would reside within the manufacturing facility are a topic of a separate presentation in this conference. Because of its robust nature and recent technological developments, a Piezo "drop on demand" printhead technology, which could be easily integrated with the existing packaging unit has been selected for our application. The print quality requirements have been determined based on print quality features attained by gravure printing and overall process considerations. In brief, print quality and ink requirements include the specifications shown in the following Table.

DPI	About 300 dpi for text
Print Quality	Print density comparable to gravure Dry time of less than 10 sec No smearing Print tolerance/registration 0.03" No satellites
Ink	Compatible with environmental and product integrity requirements

From the point of view of applicability, the ink has to be compatible with printhead components and has to have viscosity and surface tension within the recommended values of the print head manufacturer. From the point of view of print quality, the ink will have to interact with the printed media in such a way as to produce dense, crisp and reproducible information in the form of text or graphics.

In the early stages of print head technology identification, ink requirements (such as pigment based, no UV, etc.) and ink media interactions were taken into consideration in order to select the printing technology best matched to the target application.

As soon as the print head technology was identified, the sequence of events towards final implementation involved appreciable effort in ink formulating and trials to see how the ink interacts with different media.

Depending on the print quality and process requirements, process conditions (such as substrate temperature) may be adjusted or new inks may be formulated. Of course, there is always the option (although not highly favorable in large industrial applications for printing only variable information) to design new media that interact in a desirable way with selective inks.

Nevertheless, it is very important to have a good understanding of how inks interact with media. Such an understanding can shorten ink development cycles and help to identify critical requirements in terms of process conditions and media design. The ultimate goal, of course, is to be able, given a system of ink and media, to predict print quality based on ink and media characteristics. In addition, it is highly desirable, given specific ink characteristics, to be able to specify media properties in order to achieve a certain print quality. In our work, we are primarily interested in the interaction of inks with coated labels or board. The coating has been designed for gravure printing and is primarily composed of clay and calcium carbonate.

Drying of the ink to assure no smearing as printed packages are transferred through the packaging equipment is very critical. In general, the printed ink dries through two mechanisms: i) penetration in the porous media and ii) evaporation [4]. Evaporation is important for volatile inks or when printing is accompanied by heating of the media.

The physics of penetration of liquids into porous materials is usually described by a Lucas –Washburn Equation[4] that relates the rate of penetration to the size of the absorbing capillaries, the surface tension of the ink, and the contact angle of the ink on the substrate. The rate of penetration for ideal capillary systems is usually significantly lower than actual penetration rates.[5,6] A number of other models, based on theoretical, empirical and phenomenological (based on diffusion concepts) formulations have been suggested to correct for deviations from the ideal cylindrical capillary models.[4,7]

Regarding print quality, a number of subjective and objective tests have been used in digital printing to characterize it.[10,11] Edge sharpness, solid density and contrast are some of the most commonly used qualities. More involved analysis to obtain a modulation transfer function is also used to gauge the effects of ink media interactions on print quality.

Experimentally determined print quality variables are usually correlated to ink penetration rates [4, 8, 9] and in general, a fast penetrating ink on uncoated paper will have excessive feathering and show through. The situation can be different on coated substrates that for digital printing are usually composed of high surface area pigments and hydrophilic binders. Print quality is nevertheless determined by how the ink spreads on the surface of the printed substrate, how the ink penetrates within the substrate, how long it takes for the ink to penetrate in the substrate, how the ink interacts with the binder system in the substrate, how neighboring ink droplets interact with each other, the nature of the ink, etc.

Print Quality of Ink Jet Prints on Coated Paper

Various size text characters were printed on a web rewinder system using a 240 dpi continuous binary ink jet printer, a 180 dpi shear mode DOD (referred to as DOD1) and a 94 dpi shear mode DOD (referred to as DOD2) system. All systems operated with an encoder to maintain print dimensions as web speed increased. The throw distance for the DOD head was on the order of 1-2 mm, while web speed varied from 50 to about 300 fpm. Other prints printed using other methods were also examined. The resolution for the DOD2 system was increased by pivoting the print head.

Contrast/Ink Density:

The contrast of prints on clay coated labels was evaluated by looking at the gray scale histogram produced by the digitized image of a text character (in this case the letter I) centered in the CCD camera view. The same lighting conditions and same magnification were used for both CIJ and DOD prints. Figure 1 shows the digitized pixel histograms for text printed at 50 fpm. The distance between the peak at low reflectance or low pixel intensity values and the peak at high reflectance or high pixel intensity values corresponds to the contrast between the dark text and the light substrate. It appears from this analysis (and in agreement with subjective evaluations) that the DOD print has slightly higher contrast. Contrast, of course would depend on the amount of ink deposited and its colorant nature and concentration, the color of the substrate and the penetration of the ink colorant into the substrate. This type of analysis for contrast could be used to optimize ink formulations and media to achieve desirable print quality.

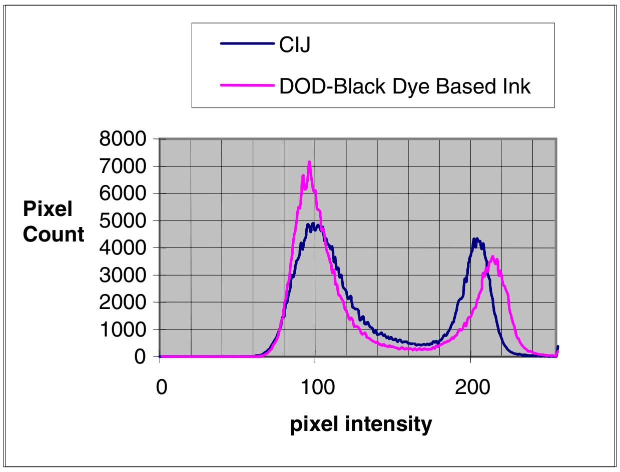


Figure 1. Contrast for CIJ and DOD1 prints on clay coated label at 50 fpm.

Similarly, by examining a digitized histogram of a solid ink area and considering the peak pixel intensity and the breadth of the pixel intensity distribution, we can draw conclusions on the density of the print and its uniformity, respectively. Table I shows estimations of the density of the solid ink areas; lower numbers are indicative of a denser image.

Sharpness:

The print quality of characters or lines was examined for prints produced by the different methods. Under most conditions of printing, the left and right sides of vertical lines examined for print quality were not the same. Edge analysis involved the following parameters:

1. Edge acutance, which was evaluated from x-profile histogram analysis of text characters by measuring the distance, in pixel columns, of the pixel intensity at 10% and 90% of the minimum plateau from the high value plateau.

2. An analysis where the digitized data along the edge were differentiated (by taking the forward difference) and the differential data were fit to a smooth curve to yield an estimate of the line spread function (LSF) which is also a measure of edge blurriness.

3. In a different type of analysis, the x-profile of a narrow stripe at the edge was measured and the data were fit to a straight line. The standard deviation of the residuals from the line fit to the data of the edge profile was used to estimate edge raggedness.

Table I (see last page) shows these various parameters estimated for various print methods. The standard deviation of the residuals in Table I indicate that the right edge of the DOD1 print at 50 fpm is not the same as that on the left side. The left edge appears more ragged due to the presence of satellites as shown in the section that follows. As web speed increased the satellites, which have a speed lower than that of the main drops, fall progressively further away from the main drops in a direction opposite to that of the web movement.

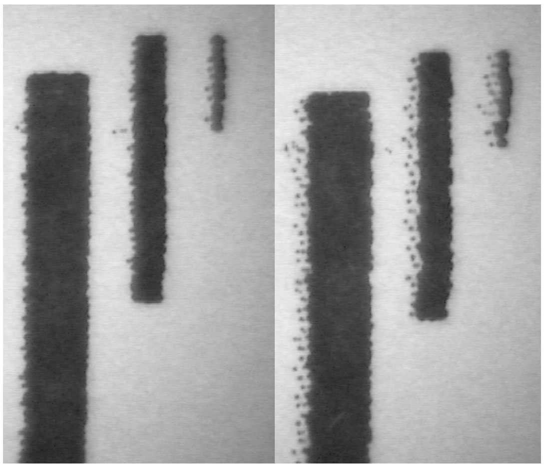
The CIJ prints appear sharp with similar left and right edges at web speeds of about 50 fpm. At higher speeds, the edges deteriorate due to smearing on the transfer roll from print to rewind. It takes longer for the water based ink of the CIJ printer to dry on the clay coated label as compared to the solvent based DOD ink that shows no ink smearing.

The gravure printed conventional label had rough edges the size of the gravure cells. Prints with a SOHO DOD printer were printed from TIF files of 300 and 600 dpi resolution, respectively on both clay coated labels and specialty coated ink jet paper. The ragged edges were similar on both sides of the print. The raggedness was primarily due to the resolution of the graphics files. On the ink jet paper the ink dots showed small gain and stayed on the surface of the paper thus producing vivid colors. On the clay coated label the ink dots spread and penetrate in the paper producing faded prints. The inks used in the SOHO DOD printer were aqueous, dye-based inks.

The DOD UV print had very good sharpness and uniform density.

Satellites:

Prints from the DOD1 printhead showed evidence of satellite drops formed during drop ejection. At low print speeds (50 fpm) these satellites fell close to the main drops and became part of the continuous character. As print speed increased, the satellites fell progressively further away from the main drops. However, these satellites were small and not quite visible to the naked eye. Figure 2 shows the relative location of the main drops and their satellites at 50 and 100 fpm, respectively. No satellites were observed for the CIJ system.



(a) *(b)*

Figure 2.Print quality deterioration due to satellites. (a) 50 fpm, (b) 100 fpm.

It has been our experience that for certain DOD systems, the voltage at which the print head is fired as well as ink viscosity affect satellite formation. As firing voltage increases and/or ink viscosity decreases, the formation of satellites becomes more prominent.

Drying Time-Effect of Media:

The ink density or ink fill of digital prints depends of course on the dimension of the drop on the substrate, the print resolution, and the strength of the colorant. The ink dot size on the substrate depends on how the ink spreads and is significantly smaller for a specialty ink jet paper as compared to a clay-coated label.

Where ink media interactions clearly manifest their critical importance is on the dry time of the print. In our application, dry time is taken as the time required so that ink does not smear as packages go through the packaging equipment.

In systems where drying by absorption is the primary driver, ink viscosity, surface tension, media openness and porosity and affinity to the ink system are critically important. The situation can become very complicated if components of the ink formulation alter the nature of the receiving layer; small pigments may increase the flow resistance through capillaries, solvents may interact with binders, etc.

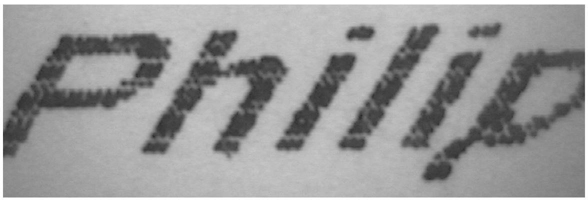
As already mentioned, ink penetration into a substrate can be phenomenologically modeled as a diffusion process.[4] The theory of straight interconnected capillaries predicts that the diffusion coefficient as a function of pore radius depends on surface tension/viscosity.[5] However, this does not seem to be the case as indicated by the experimental data in reference[5,8] of ink penetration in paper based substrates. In reference 8 faster penetration rates were realized with low surface tension inks due to improved wetting.

In addition, process conditions appear to have a significant impact on drying time, as they also affect ink media interactions. The penetration rate can be significantly improved by raising the temperature of the printed substrate.[8] An increase in temperature by 30% produced a 1.4 to 2.3 time increase in diffusion coefficients.[8] We have experimented with raising the temperature of the substrate in an attempt to accelerate dry time and eliminate smearing.

The following images show the print quality achieved for a number of oil based inks on coated board.

In the previous image the ink dries slowly and spreading and ink density variability are evident. By changing ink formulation, print quality improved as shown in the following, however drop volume and drying time were still excessive.

When the firing voltage decreased to reduce drop volume and improve dry time, incomplete fill was observed.



The best print with improved dry time was achieved by firing at the low voltage on a preheated substrate.

Dry time depends of course on drop volume. At room temperature, the above images, at the higher voltage, take about 25 seconds to dry. At the lower voltage, dry time reduces to about 15 seconds and is less than 10 seconds if the substrate is preheated. The following table shows some theoretical calculations assuming drying can be modeled by diffusion.[4] It is shown that by increasing drop diameter by 20%, dry time increases by more than 40%. Similarly, decreasing the openness of the ink receiving layer can significantly decrease dry time.

Void fraction in receiving layer	Drop Diameter μm	Diffusion Coefficient μm^2/sec	Dry time sec
0.3	60	100	10.3
0.3	50	100	7.0
0.3	50	200	3.7
0.57	50	100	2.0

Increasing substrate temperature and thus increasing the phenomenological diffusion coefficient decreases dry time. Some of the oil based inks tested on clay coated paper have viscosities with apparent activation energies $E\alpha/R$ of about 3000 K. By increasing the substrate temperature from 30 to 50 deg C, ink viscosity decreases by about half while the diffusion coefficient (assuming an inverse dependency on viscosity) almost doubles reducing dry time to about half. This estimation seems to agree with our qualitative observations on dry time as substrate temperature increases.

Conclusion

A number of metrics can be used to gauge print quality of digital prints and supplement subjective evaluations. Water based inks and oil based inks can both be used to print on clay coated paper, however dye based prints appear less dense and less uniform as compared to pigment based inks. Satellites in DOD systems deteriorate print quality. These satellites are critical in high speed processes and seem to form more readily at the low end of ink viscosities and at high firing voltages. The absorption of ink by the media is complicated by physicochemical interactions between ink and media components, respectively. Clay coated papers do not seem to offer enough porosity for fast drying. Drying is rather slow but can be significantly improved by preheating the substrate.

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Biography

Georgios Karles received his Ph.D. in CHE from the University of Texas at Austin in 1990. He then worked at the University of Texas as a postdoctoral fellow investigating heterogeneous catalysis. From 1992 to 1997 he was with International Paper in Tuxedo, NY working on developing papers with tailor made properties through chemical or physical modifications. George has been with Philip Morris since 1997 working on specifications for packaging materials and assessing and implementing new packaging and printing technologies.

Henry M. Dante is currently at Philip Morris research and development where he is responsible for implementing digital printing technologies. He received his Ph. D. in Electrical Communication Engineering from Indian Institute of Science, Bangalore and worked as a faculty member in the Electrical Engineering Department at KREC in India and at Tufts University, Medford. He has been with Philip Morris from 1988 where he has worked on developing vision systems, process control, modeling and simulation and implementing new technology.

Table I. Print quality analysis results.

		Ink	Standard deviation of residuals	Edge distance from 10% to 90% of minimum	LSF mid point width	Most Frequent Pixel intensity From Histograms/Subjective evaluations
	Viscosity, cP	Surface tension, dyn/cm	right side/left side	Right/left		
DOD1-50 fpm	8.6	Oil based	451.9/937.83	66/33	21	70/Good contrast/Broad density/ fair to good quality
CIJ-50 fpm	1.3	43.3 water based	291.55/254.86	60/28	15	60/Good contrast/Broad density/ Fair to good quality
DOD1-100 fpm	8.6	Oil based	751.43/	27/116	36	80/Fair (sattellites)
CIJ-100 fpm	1.3	43.3	272.21/462.59			91/Fair
Gravure print	gravure		843.93/	53/130	35	49/Very good ink density/Narrow density/ Good contrast
SOHO-300 dpi-IJ Paper	2.8	Water based	908.7/1026.2			Good contrast/ Good quality
SOHO-600 dpi-IJ Paper	2.8	Water based	702.1/800.7			Good contrast/ Good quality
SOHO-600 dpi-PM label	2.8	Water based	415.8/437.5	12/36	18	66/Fair (faded-low ink density)
DOD2 UV single pass	12-14	UV	169.4/252.3			82/Good contrast/Good quality
DOD2 ~300 dpi on preheated coated board	12-14	Oil based		11/13	14	52/Very good ink density/narrow density/ good contrast