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The Effect of Substrate Properties on Print Attributes for Gravure Printing - From Proof to Press

Yu Ju Wu
Western Michigan University

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THE EFFECT OF SUBSTRATE PROPERTIES ON PRINT ATTRIBUTES FOR GRAVURE PRINTING – FROM PROOF TO PRESS

by

Yu Ju Wu

A Dissertation
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy

Department of Paper Engineering, Chemical Engineering, and Imaging
Dr. Alexandra Pekarovicova, Advisor

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Yu Ju Wu
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CHAPTER 1
INTRODUCTION

Printing is a complex process, which involves a number of variables such as image carriers, inks, print media (substrate), and operation of the press. The quality of final prints and color reproduction capability are determined by the successful integration of all variables involved in the printing process.

Substrate is a crucial variable in predicting and reproducing color and has significant influence on the print quality such as print contrast, density, color, and tonal range. The interaction between paper and ink, its porosity, surface smoothness, together with optical properties such as whiteness, opacity, light scattering, and gloss must be considered in the printing process\(^1\).\(^2\).\(^3\)

Gravure is the major printing process used for publication such as long-run magazines, catalogs, newspaper, and miscellaneous commercial printing. In the gravure printing process, compressibility and surface smoothness are two important paper property requirements for high print quality\(^4\).\(^5\).\(^6\). Most gravure publication substrates are coated to meet the needs for smoothness, gloss and printing performance. Changes in coating formulations such as pigment composition, type and amount of binder and additives produce different coating layer microstructures. These surface properties of paper are governed by coating layer, which in turn affect ink transfer, determining the color appearance of final printed result\(^7\).\(^8\).\(^9\).\(^10\).\(^11\).

In the gravure printing process, similar to all other printing processes, color proofing for the purpose of checking the color to ensure
that it is as desired, is becoming a must, especially in the field of publication printing. Before proceeding to cylinder engraving, digital files must represent perfect matches to originals. Recently, the use of ink-jet digital proofing started to grow remarkably, due to its benefits of high speed, wide color gamut, and affordable prices for a device. With its unique properties, ink-jet digital proofing provides significant time and cost savings compared to conventional procedures (preparing cylinders and printing proof samples) for potential product verification\textsuperscript{12,13}.

The accuracy of digital proofing (proof-press color matching) is affected by the printer, software and substrate involved in the digital proofing processes. Different types of printers utilize different ink technologies, which affect the print result. Printer control software governs how much ink can be deposited onto the paper surface. Some digital printers combine with advanced color-matching software to offer a better color match. Print media is a significant variable in the digital proofing process. Generally, proofing is done using the substrate that will be used for actual product printing. Proofing on the actual production stock more closely predicts both look and feel of print outcome. However, working with different inks and devices, the same actual production printing substrate can have a very different color gamut and behave differently in the digital proofing process, which in turn affects the proof-press color matching result. The paper properties determine ink and paper interactions and absorption behavior, which in turn influences the density levels and the size/shape of color gamut, affecting the quality of the printed result. Therefore, optimal digital proofing must factor the paper into the color reproduction process\textsuperscript{14,15,16,17,18}. 
Since paper is one important determinant of print quality in either printing or digital proofing processes, it is important that all paper properties are well defined and controlled, thereby uniformity of printing and good color reproduction performance can be obtained. The aim and purpose of this work was to:

- To characterize most important substrate properties affecting color reproduction;
- To formulate coatings for LWC papers, which will give larger color gamut and better print quality in publication gravure printing;
- To formulate coatings which will give larger color gamut in digital printing;
- Be able to match digital proofs to gravure process and spot color prints.
CHAPTER 2
LITERATURE REVIEW

Paper properties are probably the important factors affecting the completeness of image transfer and image appearance in the printing process. This section reviews the gravure publication printing and digital proofing systems, together with paper coating formulations and properties of paper. A discussion of important print attributes dealing with quality of print is also included.

2.1. Overview of Gravure Printing

As one of primary printing process, gravure is a process commonly chosen by publishers and advertisers, due to its unique properties of simplicity of the process, consistent print quality and color reproduction for medium to long print runs, and capability of producing photographic quality multicolor reproduction\textsuperscript{5, 20}.

Table 1 lists the forecast market shares of the major print technologies (excluding packaging) to the year 2010. So far, the majority of printing job is done by the lithographic printing technology, but the gravure printing has a constant market share with around 20\% due to its high printing quality and capability of long-runs. Up to 2010, the market share of gravure printing will decrease slightly because of the growth of digital printing\textsuperscript{21}. In addition to short-run production, digital printing can be also used for high-quality contract proofing. As digital proofing integrates into its process, gravure printing can take the advantage of significant time and cost savings.
Table 1. Forecast market share of print processes (excluding packaging) %

<table>
<thead>
<tr>
<th>Process</th>
<th>2002</th>
<th>2006</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litho</td>
<td>61</td>
<td>59</td>
<td>57</td>
</tr>
<tr>
<td>Gravure</td>
<td>22</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>Digital</td>
<td>5</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Desktop</td>
<td>5</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Other (flexo, screen, letterpress)</td>
<td>7</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>


2.1.1. Principle of Gravure Printing

The ink fountain, image carrier (engraved cylinder), impression roller, and doctor blade are four principle components of each gravure printing unit. The engraved cylinder is a unique image carrier, where the image to be reproduced is etched or engraved in the form of small wells or cells, so that print areas are below the surface of the cylinder. In this printing process, the engraved cylinder rotates in the ink fountain (a tank of fluid ink) allowing the engraved cells to become filled with ink. The excess inks are wiped from the surface of the engraved cylinder by the doctor blade, leaving ink only in the engraved cells (image areas). The ink in the engraved cells then transfers from the engraved image to the substrate with the assistance of the impression roller, so that the ink is drawn out of the engraved cells via capillary action. The generic gravure printing unit is shown in Figure 1. The gravure printing process can be used in a variety of applications, such as film, foil, light weight coated paper, newsprint, and paperboard printing. It also can be applied in floor coverings and vinyl product reproduction⁴⁵⁻²².
2.1.2. Properties Required for Gravure Publication Paper

Much publication printing, such as long-run magazine, catalogs, newspaper inserts, and miscellaneous commercial printing is completed by using gravure printing. Gravure printing is well known for high quality color reproduction on different grades of publication papers (e.g., light weight coated paper, supercalendered paper, free sheet, or newsprint). The most important property requirements of gravure paper include smoothness, compressibility, and good formation of paper. The surface smoothness together with the overall printing smoothness (compressibility) is the key in obtaining good ink transfer.

The paper surface quality (surface smoothness) controls how the paper surface contacts the ink film during printing. In the gravure printing process, image reproduction is done by transferring inks from the engraved cells (image carrier) to the paper surface. The combination of capillary action and the pressure of the impression cylinder take place to transfer the ink. Adequate contact between the paper surface and ink results in complete image transfer. If a rougher paper surface, consisting
of hills and valleys or pits and cavities is used, the ink may not transfer properly and more ink is required for printing, causing excessive show through and poor halftone dot reproduction, which results in broken or incomplete images. Also, increased printing pressure can lead to defect of print mottle\textsuperscript{6,23}.

The other essential feature of gravure paper is compressibility. Resiliency is important for good printing, since gravure presses apply very high impression pressures. Compressibility can be classified as bulk compressibility and surface compressibility. The effects of bulk compressibility are governed by the sheet thickness. The thicker paper with too dense coated layer may result in poor ink transfer. Surface compressibility controls the reduction in roughness with the use of pressure on the paper surface. A soft compressible paper will deliver better print out. The application of surface sizing may reduce surface compressibility\textsuperscript{6,23}.

Some optical properties such as brightness, opacity, and paper color are also essential for gravure publication printing. Both brightness and paper color contribute to the subjective impression of paper brightness and print contrast. Opacity is crucial property for publication papers because they are usually printed on both sides. The higher intensity of light is scattering off the paper surface, the higher is the opacity the less is the show through\textsuperscript{5}.

2.2. Digital Proofing System for Gravure Printing

Color proofing is done for the purpose of checking the color to ensure that it is as desired, before proceeding to the cylinder engraving. The printer and the customer make a contract based on the proof, which is
the so-called “contract proof.” The contact proof needs to predict how the
print is going to look on press. Therefore, the contract proof should be as
close as possible to the final printed result concerning the content
as well as color fidelity. A proofing solution also needs to provide good
spot color matching, because packaging and product printers require the
creation of economical proofs for spot colors.

In the past, proofing was done by using a gravure proofing press,
using the same ink and substrate, which represented higher cost, because
the image carrier needed to be engraved prior to proofing. Engraving was
verified and cylinders for press run engraved and proofed again, which
was time consuming process.

Recently, new developments in digital printing have made it
possible to produce small quantities of high-quality color products at
affordable prices, creating an alternative for short run, low cost, on-
demand printing. For example, ink-jet printing can be used to produce
short runs of packaging-samples in an effective way. Its unique properties
enable an ink-jet printer to be used for pre-press proofing in commercial
printing application. Digital proofing is produced directly from digital
data by printing on color thermal transfer, ink-jet, or electrophotographic
printers. With the aid of color management, digital printers can simulate
the final press sheets by using ICC profiles. Also, with its advantages of
high speed, wide color gamut, and affordable prices for a device, digital
printers provide significant time and cost savings compared to
conventional gravure proofs.

At present, ink-jet-based digital proofing systems are becoming
more and more accepted for digital proofing; representing more than 60%
of the market on a worldwide basis, and it is still growing.
2.2.1 Principle of Ink-jet Digital Printing

The principle of ink-jet printing is producing small droplets of ink from a nozzle onto the paper surface directly. Droplets are formed when controlled pressure is applied to the liquid ink in its reservoir as it flows into the printing nozzles. This is achieved by applying various technologies, which include continuous stream printing and drop-on-demand\textsuperscript{22, 32, 33}.

The ink-jet digital proofing devices used in this study are an Epson Stylus Pro 4000 printer, an Epson Stylus Pro 9800 printer, and a Canon PIXMA Pro 9000 printer. These printers apply drop-on-demand technology to form droplets on the paper surface. The feature of drop-on-demand ink-jet is that the droplets are generated only when they are required, thereby eliminating the need to control excess droplets, together with the guttering and re-circulation. Piezoelectric technology is a simple method to generate drops electronically and is wildly used in drop-on-demand ink-jet. The digital signal changes by using a piezoelectric effect. The piezoelectric effect is a phenomenon in which small electronic impulses are sent to suitable crystalline materials causing them to expand. Therefore, the piezoelectric effect\textsuperscript{21} can cause pressure pulses so that droplets are generated intermittently according to the electronic signals received. Drop-on-demand technology has advantages of mechanical simplicity, low hardware cost, and simplified logic. Also, it requires simpler ink formulations, because they do not need to be conductive. However, DOD technologies are sensitive to substrate and vibration and have slower dot ejection rates\textsuperscript{21, 22, 32, 33, 34}. The schematic diagram of drop-on-demand ink-jet is shown in Figure 2.
2.2.2. Ink-jet Digital Proofing System

Ink-jet printers work with spectral characteristics of the colorants and the printed results could differ from a printing press. In digital printing, colors are numbers. Serving as a digital proofing system, the key to matching proof to press is how accurately the digital color numbers can be manipulated in comparison to printing characteristics. With the aid of color management, the flexibility of digital data processing allows digital proofs to simulate printing presses with an ink-jet printer.27,35,36

The main components of the ink-jet digital proofing system include the ink-jet printer, inks, print media and printer control software with color management system (CMS). The accuracy of proof-press color matching is affected by all of the components involved in digital proofing processes.12,37,38 There are ongoing developments about new proofing technology to meet the requirements such as spot color reproduction, paper color, gloss influence, remote proofing.39

The basic requirements for a digital contract proofing system include color consistency, color fastness, wider color gamut, and efficient color manipulation. A contact proof printed from the same data should have same output all the time. The proof cannot fade, at least for a certain
period of time. In addition, a wider color gamut and efficient color manipulation are essential for the accuracy of color matching27.

2.2.2.1. Ink-jet Inks

Ink-jet inks are very different from press inks. Typically, two functional components of all inks, including ink-jets, are the colorants and the vehicle. The function of colorants, either dye or pigment, is to provide color, while the function of ink vehicle is to deliver colorant to the paper. By far, the inks used for desktop and larger format applications are water based, primarily due to aqueous inks are more environmentally friendly and meet worldwide health and safety regulations. In addition, UV inkjet technology is very popular, and most widely used, especially in digital packaging applications. Impulse-jet printers require a high boiling point fluid by using water based inks. Therefore, ink vehicle in ink-jet printers is mostly purified water, while the colorant is only about 5 to 10% of the ink by weight. In addition, small amounts of additives may be added to improve the ink performance. For example, surfactants are added to achieve a satisfactory surface tension level. The use of humectants can minimize the effects of viscosity plugs in the nozzles. Co-solvents help keeping dyes in solution and pigments in suspension. Ink pH can be controlled within a narrow value by using buffering agents. Biocides and fungicides are used to prevent growth of microorganisms in the ink during storage and use30, 34, 40.

For successful ink-jet printing, inks cannot dry within the nozzle to prevent nozzle clogging. However, once ink droplets are ejected, they must rapidly wet and penetrate the surface to control dot spread, meanwhile, they must dry fast enough on the paper to minimize
feathering in the paper fibers. After coming in touch with the paper surface, the ink vehicle separates from the colorant, leaving colorant near the surface to impart optical density. The design of ink-jet ink formulations needs to take diverse attributes into consideration. The attributes of ink-jet ink include viscosity, surface tension, drying time, drop flight, corrosive properties, fade resistance, compatibility with printing surfaces, etc. Usually, desktop ink-jet printers have a viscosity of between 1.5 and 3 centipoises\textsuperscript{30}. Ink viscosity needs to be adjusted to provide best performance. Pigment particles, for instance, could make the ink too viscous and might cause nozzles clogging. The surface tension of ink-jet ink is usually controlled in the range of 20 to 30 dynes/cm\textsuperscript{30}. Since the nozzles are exposed to air, ink surface tension and viscosity must be maintained within narrow limits to ensure proper drop volume, velocity, and trajectory\textsuperscript{30,34,40}.

Ink-jet printers offer both dye and pigment colorants. Each type has its unique properties and is suitable for certain applications. Dyes are molecules that are chemically dissolved in the ink vehicle. Compared to pigments, dye molecules are capable of producing brighter color and larger color gamut, due to their very small particle size. However, after printing, internal chemical bonds in dye molecules can break as a result of exposure to light, moisture, oxygen, and other environmental chemicals. Therefore, lightfastness and waterfastness of the print may not be good. Pigments for inkjet printing are particles with diameter of about 50 to 150 nanometers\textsuperscript{41}. Pigment particles are not dissolved in the ink vehicle, instead, they suspend with dispersing agents. Pigments impart color by forming a thin film on the paper surface. Since they are too large to penetrate most ink-jet papers, pigment particles stay on the paper surface
and it is difficult to achieve a uniform gloss, resulting in weak and dull appearance when viewed at certain angles. Pigments are well known for offering excellent fade resistance.\textsuperscript{30, 34, 40, 41}

The Epson Stylus Pro 4000 ink jet printer is used with UltraChrome pigmented inks consisting of seven color ink set, whereas the Epson Stylus Pro 9800 ink jet printer was used with UltraChrome K3 inks consisting of eight color ink set (as shown in Figure 3). UltraChrome K3 ink technology with three-level black ink is designed to replace the previous Epson UltraChrome inks. The only ink that is the same as the UltraChrome ink set is the Matte Black.\textsuperscript{42, 43} Basically, UltraChrome inks combine the advantages of both dye and pigment based inks in their formulations, where each pigment particle is encapsulated in a resin. The use of light magenta and light cyan inks, combined with dark cyan and dark magenta inks, is for the purpose of producing a smoother tone scale. This technology offers many advantages including uniform particle shape and particle size, greater color gamut, advanced optical density, etc.\textsuperscript{40, 41, 42, 43}

![Epson Stylus Pro 4000 Ink Set](image)

![Epson Stylus Pro 9800 Ink Set](image)

Figure 3. Ink set for Epson ink-jet printers

2.2.2. Print Media

The properties of print media are the crucial determining factors for the quality of color matching. Color matching quality as well as the detail
rendering and the text quality are affected by color gamut and color stability of proofing systems, which are strongly media dependent\textsuperscript{39, 44}.

The surface properties of print media and the attributes of the base paper play a decisive role in the digital proofing output. The physical properties of ink-jet media control the spreading, penetration, and absorption of ink, while the porosity and sizing degree of the base paper determine the rate of ink droplet penetration into the fiber network\textsuperscript{30, 39, 45}.

Ink-paper interaction governs the ink receptivity of the paper. The ink droplets need to strike in quickly enough to prevent print defects such as bleeding and feathering. Ink-jet print media usually contain a coating layer to control the absorbency of the paper. High absorbency is usually results from a rough paper surface and tends to drain the ink vehicle into the pores, resulting in dull ink films. Low absorbency is usually associated with a smooth paper surface, offering high ink holdout and giving a smooth and glossy print with high print density. The coating layer is primary determinant of surface gloss, dot shape, optical density, overall image brightness and hue; ink capability, and dry time. It also plays a significant role in print fade resistance and waterfastness\textsuperscript{30, 45}.

Generally, a contract proof is done using the substrate that will be used for actual product printing. Proofing on the actual production stock more closely predicts “look and feel” of print outcome. However, working with different inks and devices, the actual production printing substrate can have a very different color gamut and behave differently in digital proofing\textsuperscript{14, 15, 41, 45, 46}. When the digital printer is to be used for proofing, the interaction between paper and ink, its porosity, roughness, coating structure, together with paper properties such as whiteness, light scattering, and gloss must be considered in the digital proofing process.
These characteristics may differ significantly from the ideal/manufacturer recommended substrate. It is important to select a paper type with suitable paper properties to obtain better printability. Technically, the selected paper should enable the ink-jet printer to produce a good range of tone scale, so fine details can be reproduced. Usually, digital contract proofing, working with high quality ink-jet media, can deliver higher densities, larger color gamut, higher color stability, and higher image sharpness.

2.2.2.3. Printer Control Software

Functionally, there are two kinds of software to control a printer. The first one is the printer driver (ink-jet printer manufacturer’s software); the other one is third-party raster imaging processor (RIP) software. The application of an RGB or CMYK device will depend on the user’s workflow.

Printer driver software generally drives the printer to print data files in RGB mode. An RGB printer can be controlled by three channels. A user sends an RGB image and the printer driver performs the conversion from RGB to CMYK. PostScript printer drivers actually fall into the latter category, since the specification requires the ability to process CMYK data among other color spaces. Gutenprint provides a set of CMYK printer drivers for UNIX-based systems (MacOSX, Linux, etc.) that provide open source PostScript support when combined with CUPS (Common UNIX Printing System).

Third-party raster imaging processor (RIP) software interprets raster and vector data files for a specific postscript printer in either RGB or CMYK mode. During the processing, digital data are sent to a RIP and the
PostScript page description is interpreted. Those page components, raster and vector images are then translated into bitmapped data files, so that a specific output device can understand and deliver commands to control the actions of the output. By controlling CMYK inks directly, RIP software can provide better control for accurate digital color reproduction.

The functions of a RIP include generating halftones, preparing color separations, and handling color management tasks. Through color separation process, the RGB components of each pixel in the original image are converted to CMYK or even spot color components, coming with a black generation procedure to control and reduce the coverage of inks for the printing surface. Some RIPs offer the function of device calibration for creating repeatable and predictable printer behavior. The linearization process allows an ink-jet printer to distribute the right amount of inks on the substrate. Because ink is distributed correctly on the media, a larger color gamut can be obtained. Moreover, RIPs can characterize an output device and therefore achieve the most accurate color matching by integrating with third-party ICC-profiling software and hardware. With built-in color management functions, the color space can be defined in software at the prepress and RIPping stage to optimize the end result.

2.2.2.4. Color Matching

Color management is designed to meet the need of open-systems and cross-media color reproduction workflows with the goal of maintaining color appearance. The International Color Consortium (ICC) committee standardizes the ICC profile structure for describing input and output devices. ICC profiles are main components of the color
management workflow. Image processing operations such as color transformations, color separations, rendering intent, etc., highly depend upon the information in the ICC profiles and the calculations performed by using color management module (CMM)\textsuperscript{15, 30}. Typically, the CMM processing uses a pair of profiles, one referring to the source device and the other referring to the destination device.

Technically, each device has its own profile. The conversion of color information usually goes through several color transformations. The transformation coefficients are derived from the tags of the input and output profiles. A general approach of ICC color management is shown as below. First, an RGB image uses one-dimensional lookup tables to linearize an input RGB signal (Equation 1). The linear RGB values are then transformed to XYZ with a 3*3 matrix (Equation 2)\textsuperscript{30}. In order to convert color information, XYZ tristimulus values are further transformed to \( L^*a^*b^* \) values (Equation 3)\textsuperscript{35}.

\[
\begin{align*}
[R'] &= \text{LUT}_{R \rightarrow R'} [R] \\
[G'] &= \text{LUT}_{G \rightarrow G'} [G] \\
[B'] &= \text{LUT}_{B \rightarrow B'} [B]
\end{align*}
\]

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
R' \\
G' \\
B'
\end{bmatrix}
\]  

(1)  

(2)  

Where RGB represent the digital values of the source device, \( a_{ij} \) are the matrix coefficients to estimate colorimetric values, and XYZ represent the tristimulus values for a sample under a given illuminant.

\[
L^* = 116 \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - 16 \quad \text{if} \quad \frac{Y}{Y_n} \geq 216/24389
\]
\[ a^* = 500 \left( \left( \frac{X}{X_n} \right)^{\frac{1}{3}} - \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} \right) \quad \text{if} \quad \frac{X}{X_n} \geq 216/24389 \]
\[ b^* = 200 \left( \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - \left( \frac{Z}{Z_n} \right)^{\frac{1}{3}} \right) \quad \text{if} \quad \frac{Z}{Z_n} \geq 216/24389 \]  

(3)

Where \( X, Y, Z \) are the tristimulus values of the sample, \( X_n, Y_n, \) and \( Z_n \) are the tristimulus values of the reference illuminant, and \( L^*, a^*, b^* \) values are the colorimetric data used in profile connection spaces.

The forward process involves converting device independent values (\( L^*, a^*, b^* \) values) into destination device dependent values (CMYK) by using Equations 4 through 6. In Equation 4, \( L^*a^*b^* \) values are modified through individual one-dimensional lookup tables. The modified \( L^*a^*b^* \) values are then transformed to linearized cyan, magenta, yellow, black values by using Equation 5. Finally, Equation 6 is utilized to form the CMYK signals for the destination printer.

\[
\begin{align*}
[L^*'] &= LUT_{L^* \rightarrow L'} [L^*] \\
[a^*'] &= LUT_{a^* \rightarrow a'} [a^*] \\
[b^*'] &= LUT_{b^* \rightarrow b'} [b^*]
\end{align*}
\]  

(4)

\[
\begin{bmatrix} C' \\
M' \\
Y' \\
K'
\end{bmatrix} = LUT_{Lab' \rightarrow CMYK}[L', a', b']
\]

(5)

\[
\begin{align*}
[C] &= LUT_{C \rightarrow C'} [C'] \\
[M] &= LUT_{M \rightarrow M'} [M'] \\
[Y] &= LUT_{Y \rightarrow Y'} [Y'] \\
[K] &= LUT_{K \rightarrow K'} [K']
\end{align*}
\]  

(6)

When it comes to an ink-jet printer matching a press, the effective RIP configuration and color gamut mapping by using profiles to do the conversion work is the key to obtain good color matching results. It relies
highly on the color management and requires an optimized system approach of matching the printers, inks, and paper through the color management. The principle of proof-press color matching is to transform the characterization of the proofer into the characterization of the printing press. The digital proofer uses press characterization as the target color output for its proof. Spot color reproduction is also an important portion of digital proofing. A wide color gamut has made it possible to produce accurate spot colors\textsuperscript{15, 26, 27}.

2. 3. Paper Coating

Paper is an absorbent substrate, which absorbs printing ink to a certain extent. Since untreated paper can allow excessive penetration of ink, coatings are applied to hold the colorant near the surface for achieving high color density and minimizing strikethrough. The paper coating is a composite material consisting of pigment, binder and small amounts of performance enhancing additives along with air-filled voids. The pigment particles are bound together by binder in a porous network. Their arrangement on the base paper makes up the coating structure. Changes in pigment composition, type and amount of binder and additives produce different coating layer microstructures. The coating structure in turn affects ink setting speed and ink layer uniformity, which are important in achieving high print quality. Technically, the coating layer provides two primarily functions: to absorb the ink vehicles and to control the ink spreading and penetration\textsuperscript{7, 8, 9, 10, 11, 15, 40}. 
2.3.1. LWC Paper Coating

Light weight coated paper (LWC), one of the most widely used gravure publication grades, has a coating layer applied on the base paper sheet to mask the roughness and void spaces, providing a smooth surface that gives a uniform and defect free image when printed. The coating layer covers the fibers and voids to improve paper properties such as brightness, gloss, smoothness and uniformity. The coating layer also improves the print quality by holding the ink on the surface of the paper and by providing a uniform smooth surface for creating a detailed uniform printed image.\(^7\)\(^{53}\).

Latex polymers, most widely used as pigment binders for various types of coated papers, are used for the purpose of binding the pigment particles to each other, binding the coating components to the base stock, providing the required strength for the coated paper to pass through the printing and converting operations, and yielding improved sheet gloss, ink gloss and printability.\(^54\)\(^{55}\). The mechanical properties of the coating layer depend not only on the cohesion of the latex bridges formed between the pigment particles, but also the adhesion between the latex and pigment particles and void structure of the coating layer. Indeed, pore structure is mainly affected by pigments, their size and shape, but the location of latex in the structure may also influence the final paper properties. Furthermore, the type of latex used in the coating formulation will affect the strength and absorbency characteristics of the coated paper. These coating characteristics determine the rate of ink penetration and amount of ink transferred to the paper. Experiments continue to be designed to provide the appropriate paper and ink interaction and
produce high quality images to meet printing and paper manufacturing

2. 3. 2. Ink-jet Paper Coating

Ink-jet printing technology is widely used in commercial large format and desktop small format printing for photo, graphic art, document, and serving as a valuable proofing device. The present ink systems used for ink-jet printing are water based ones, containing up to 95% water. In order to absorb ink quickly and produce high-quality color images with ink-jet printers, specialty media are required. Ink-jet paper employs a surface coating to modify the paper surface structure and properties to provide better ink-jet ink receptivity, in order to achieve high print quality and image stability. The design of ink-jet coating is for the purpose of providing a number of important properties, such as instant ink absorption, gloss, optical density, wider color gamut, adhesion to the substrate, and defect-free printing on the media. The designed coating determines the mechanism of ink absorption, which in turn governs the ink-drying-time and color fidelity², 58, 59, 60, 61.

For photo printing, two coating technologies are currently used: swellable coatings and microporous coatings. Swellable ink-jet media typically contain water soluble polymers such as gelatin, polyvinyl alcohol (PVOH), and polyvinyl pyrrolidone (PVP) as binders, a cationic polymer to fix the dye, and a crosslinker to improve water resistance. These systems absorb ink solvents by a film swelling mechanism (diffusion of the ink), which results in slower dry times and lower risk of improper ink transfer, smudging, and ink bleed in high humidity environments⁵⁶, 58. However, swellable coatings offer advantages of high
ink capability and good-to-excellent fade resistance. Microporous coatings became the preferred technology for producing high quality instant dry glossy ink-jet paper, since to these coatings build up a porous network for the absorption of ink-solvents. As ink droplets hit the surface, capillary action pulls them quickly into the coating. Microporous coatings are comprised of inorganic oxides such as fumed silica, fumed alumina, colloidal silica, polymer binders such as PVOH, gelatin, and cationic polymers.

For the optimum ink absorption and the highest gloss, the highly structured nano-particle pigments, such as a fumed alumina and fumed silica are suitable. These materials provide special pore structures and surfaces ranging from 50-700 m²/g. Their pore sizes range between ten and several hundreds of nanometers. When printing the image, this surface serves as a carrier of dyes or pigments. At the same time, the particles form voids and capillaries in the layer due to their unique fractal structure. These voids and capillaries make it possible to absorb water from the ink droplets within fractions of a second, thereby resulting in instant drying. This instant dry performance of microporous coatings enables the use of high speed printers while achieving optimum image quality.

There are several types of amorphous silica, including fumed, colloidal, precipitated and gel. Based on the manufacturing process, silica is available in sizes ranging from less than 100 nm (such as colloidal and fumed) to greater than 1 micron (e.g. precipitated, gel). Fumed silica is the oldest commercial method to produce an amorphous silica pigment. It involves the reaction of silicon metal and gaseous dry hydrochloric acid to form silicon tetrachloride. This mixture is burned at 1000°C to produce
and condense a high purity silica pigment. The fumed silica is a very fine particle size product with high levels of microporosity. It is widely used for high performance porous ink-jet media, due to its high ink absorbing capability, hydrophilicity, and ease of modification1, 2, 58, 63, 64, 65.

Alumina is also a popular pigment used in ink-jet coating for photorealistic imaging. Similar to silica, the particle sizes of alumina are in the range of 100 nm to 1 micron. It is easy to disperse, easy to stabilize in water, provides high absorption capacity, high gloss, and large color gamut, resulting in high quality prints. Alumina particles form intraaggregate pores, because there is space left in between adjacent single primary particles. These pores are needed to provide absorption capacity1, 2, 64.

Usually, ink-jet colorants (dyes or pigments) have negative charge, therefore, it is preferred that the coating layer have a positive charge to fix the ink dye or pigment to the surface. The ionic nature of the coating pigment attracted the negatively charged dye molecules or pigment and keep them nearer to the surface, meanwhile, allowing the ink vehicles (mostly water) to penetrate into the paper40, 62, 66. Alumina particles have a cationic charge. For silica, a new technique employs a surface modification with special cationic polymers, resulting in a zeta potential curve nearly identical to the curve for alumina. These cationically modified silica nanoparticles are used in glossy topcoats because of their glossing potential and compatibility with cationic additives64.

Binders used in coating formulations are responsible for the binding of the pigment particles to the base sheet and the binding of pigment particles to each other. Polyvinyl alcohol (PVOH) is the preferred binder for ink-jet coatings, because it ensures a fast set-off, good water
resistance of the prints, and provides high brilliance of colors. Polyvinyl pyrrolidone (PVP) is another binder used for ink-jet coatings. It is a hygroscopic, amorphous polymer, which is soluble in water and other polar solvents. In solution, it has excellent wetting properties and readily forms films. Because of its polarity property, PVP has good performance on binding polar molecules, therefore, providing application for photo-quality ink-jet papers. Particle-to-binder ratio is one factor that needs to be taken into account. Excessive binder will lead to fill in the interstitial pores and inhibits the absorption of the ink, while insufficient binder amounts result in poor adhesion and the pigment particles tend to dust off the substrate.

2.4. Physical/Surface Properties of Paper

The physical/surface characteristics of a paper sheet depend on a variety of factors, including the nature of the fibers used and the treatments during manufacture, as well as the coating, and finishing processes. The printability of a paper surface is influenced by surface properties, such as smoothness and the surface uniformity, and the ability of paper to absorb the ink. In most cases, high print quality is associated with good formation and with smooth, compressible paper.

2.4.1. Surface Smoothness/Roughness

A smooth, uniform paper is important in high-quality image reproduction. Smoothness or roughness relates to the formation of the sheet during manufacture. Fiber morphology, treatment during stock preparation, together with the forming characteristics of the paper machine has influence on the smoothness of a paper.
Smoothness can affect ink gloss and color, as well as print contrast. A smooth and uniform surface contributes to high level of saturation of printed ink films with glossy surfaces. For unsmooth papers, paper roughness leads to micro spots of reflected white light, resulting in a lessening of print contrast and ink density. Rough paper also increases dot gain.19

Smoothness is especially important in gravure printing. A paper surface with a wild formation or insufficient compressibility can result in incomplete image transfer, and missing dots in gravure. Some of the paper roughness can be overcome in the printing nip to the degree that the paper is able to conform under pressure.19

Smoothness/roughness is commonly measured by an air-leak tester which describes the topography of the paper surface. The principle generally applied for this purpose measures the ability of the paper surface to resist an air stream flowing between the paper surface and a surface or an edge pressed against it.69 The Parker Print Surf (PPS) technique is one of the methods to measure smoothness/roughness. Other techniques used in measuring smoothness/roughness are Bendtsen tester, Sheffield tester, and Bekk tester. These devices typically measure the air flow between the paper surface and a metal edge pressed against the surface.3

When using a Parker Print-Surf tester, the test piece is supported by a backing pad made of a cork/polyester composite to simulate letterpress printing nip or a litho blanket to simulate offset and is pressed against the measuring head by a variable clamp system giving 500, 1000 or 2000 kPa clamping pressures. The resistance to the air-flow of the gap between the paper surface and the annulus is measured. This air-flow is proportional
to the cube of the width of the gap and the measured roughness is expressed as the "root mean cube gap" in micrometers\(^69,70\). Two types of deformable backing are supplied with the instrument. A hard backing, which is designed to simulate packing conditions for the printing of high-quality letterpress on gravure papers, and a soft backing recommended for offset and other letterpress grades, including newsprint. The main purpose of the backing in the Print-Surf is to uniformly distribute the clamping pressure beneath the sensing head despite local variations in paper thickness\(^70\).

Clamping pressures of about 500, 1000, 2000 kPa are possible to use, corresponding to commercial printing pressures\(^71\). According to the type of paper being tested, the recommended clamping pressure is listed in Table 2. The flow meters and the subsequent impedance measuring system were calibrated to measure roughness in absolute units over the range 0.6 to 6.0\(\mu m\).

<table>
<thead>
<tr>
<th>Printing process</th>
<th>Clamping pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Letterpress</td>
<td>2000 kPa</td>
</tr>
<tr>
<td>Offset Lithography</td>
<td>1000 or 2000 kPa</td>
</tr>
<tr>
<td>Gravure</td>
<td>500 or 1000 kPa</td>
</tr>
</tbody>
</table>

Source: *Parker Print-Surf Roughness Tester Manual* (p. 3) (Reference 71).

Air leak roughness testers measure the air flow through the gaps existing at the interface of an annulus in contact with a paper surface. The rate of air flow is measured and calibrated in terms of PPS roughness, which is expressed in absolute units of micron (\(\mu m\)). The greater the readings, the rougher the paper surface is, and vice versa\(^72,73\). For air leak measurement, air flow is proportional to the cube of the local gap through which air passes, if flow is viscous. The Parker Print-Surf roughness is
calculated from the equation as follows:

\[
G_3 = \sqrt[3]{\frac{12\eta b q_v}{l\Delta p}}
\]  \hspace{1cm} (7)

where,

\(G_3\) = paper roughness, the cube-root-mean-cube of the gap between paper and reference plane
\(\eta\) = viscosity of air at room temperature, Pa\cdot s
\(b\) = width of the measuring land, m
\(q_v\) = volume of air flowing in unit time, m\(^3\)/s
\(l\) = median length of the measuring land, m
\(\Delta p\) = pressure difference across the measuring land, Pa

The roughness, in micrometers, is equal to \(G_3 \times 10^6\). The greater the reading, the rougher the paper surface is, and vice versa.

2.4.2. Air Permeability and Porosity

A paper consists of fibers, sizing, fillers, coating, and about 50% air by volume. Some of the air is present inside the fibers, but most of it resides in pores within the sheet structure. The porosity of a paper sheet is the ratio of pore volume to total volume. Porosity is determined by shape, size, the number, and distribution of the pores in a sheet. A paper made from long fibers tends to be more porous than one made from short fibers because short fibers compact more closely under the same manufacturing conditions. Fillers occupy some of the interfiber spaces, resulting in less porous sheet. The degree of fiber refining is an important step that controls porosity during papermaking. High degree refining gives less porosity and results in a denser paper. Other factors that decrease porosity
may include surface sizing, coatings, wet pressing at the press section of the paper machine, and compaction of surface by calendering. The porosity of a paper greatly affects properties such as hardness, compressibility, resiliency, and the ability to absorb inks. Porosity also contributes significantly to the opacity and grammage of a paper.19

A mercury porosimeter, measuring the incremental increase of volume penetrated as the pressure rises, can be used for the porosity-related characteristics measurement, such as of pore size, volume, distribution and density of a material. The mercury porosimeter characterizes the porosity of a material by applying varying levels of pressure to a sample immersed in mercury. The pressure required to intrude mercury into the sample’s pores is inversely proportional to the size of the pores.75

A related property, air permeability, is defined as the property of a paper that allows air to flow through it under a pressure difference across the sheet. Air permeability is inversely related to strength properties like tensile, burst, and fold, and directly related to opacity. The air permeability is also an indicator that shows how printing inks will penetrate and spread. It indicates the impregnating properties of saturating papers and how much penetration will occur when a sheet is coated. The measurement of air permeability is commonly done with the same air leak testers that are used for making surface smoothness measurements.23

The permeability of each substrate can be calculated from the Parker Print Surf porosity value and its thickness using the following equation:76
Where $K$ is the permeability in $\mu m^2$, $Q$ is the flow rate in ml/min and $X$ is the sheet thickness in m.

2.4.3. Formation Index

Formation is a measurement of uniformity of the paper which has significant influence on paper properties. The smoothness of paper, for example, is greatly dependent on the uniformity of the paper sheet. Good formation indicates uniform fiber and filler distribution in the sheet. A wild formation will tend to have lower strength and cause greater variation in opacity and printing show-through, especially in light-weight papers. It also contributes to print mottle\textsuperscript{77}. Basically, formation is measured in the form of local variations of grammage, sheet thickness, density, or transparency. A formation index is used to evaluate formation, which is the coefficient of variation of local grammage when measured over area ($\sigma_{BW}/\overline{BW}$). A M/K system formation tester can be employed to obtain formation index, which measures variations in light transmitted through the tested sheet, as the light source scans across the sheet rapidly\textsuperscript{6, 19, 78, 79}.

2.5. Optical Properties of Paper

The optical properties of a paper influence the visual quality of the printed image and contribute to its appearance and appeal. The best color reproduction will occur with papers that are bright with uniform spectral reflection, smooth, glossy, and neutral in shade\textsuperscript{19}. The optical properties include gloss, opacity, whiteness, brightness, and paper color.

The optical properties of a paper are highly related to the interactions of light with paper. When light strikes the surface of paper, it
may be reflected, transmitted, scattered, or absorbed (as shown in Figure 4). All these may occur separately or in combination. When the angle of reflection is the same as the angle of incidence, the light reflects specularly. Gloss is related to specularly reflected light. Some incident light may penetrate through the paper, resulting in transmission. In the case of scattering or diffusing, some light falling on a paper surface penetrates to a certain depth of the paper, reflects from the boundary surfaces of particles, and emits again on the entry side. That is, the radiation occurs in all directions. The visual impression of brightness and color of the paper uses the diffusely reflected light. Some incident light absorbs into paper. The absorption depends on the wavelength of the light. Therefore, the color of paper could be examined in terms of white light interaction with the paper\(^80\).

![Figure 4: Interactions of light with paper](image)

*Figure 4. Interactions of light with paper*


### 2.5.1. Brightness

Brightness is an indicator to judge the effectiveness of removing lignin from pulp. As the bleaching is extended, more lignin is removed and the blue reflectance increases to give increases in brightness. For measuring brightness, a pad of the paper is illuminated at a 45° angle and
the reflected light is filtered so that only the blue light near 457 nm falls on the instrument's light sensor. It is important to note that because of the fact that brightness measurement samples only the blue region of the visible spectrum, a colored or tinted paper cannot be fully described in terms of brightness. Brightness has been expressed in the range of 0 to 100. Most white papers have brightness values of 60-90%. A brightness index of 90 or more indicates high-quality papers. Brightness is also important for print contrast characterization. The higher the brightness, the higher the contrast between the paper and printed image.

There are two different standards used to measure brightness: the TAPPI standard and ISO standard. TAPPI standard measures directional reflectance using a C illuminant (45°/0° geometry), whereas ISO brightness measures diffuse reflectance using a D65 illuminant (d/0° geometry). The schematic of diffuse and directional geometries of measurement is shown in Figure 5. These two standards are not interchangeable, since different instrumentations are used to take measurements.

Figure 5. Schematic of diffuse and directional geometries of measurement

Today, the paper industry tends to add Fluorescent Whitening Agents (FWA, also known as optical brightening agents) in the paper to enhance the appearance and optical performance of coated and uncoated papers. Those fluorescent additives absorb in the UV region and emit in the blue part of the spectrum, resulting in the increase of brightness of paper. Therefore, the measurement of brightness needs to take FWA into account if the paper sheet contains FWA. Measurement of the fluorescent component of its brightness can be made using an instrument containing an optional UV-absorbing filter, which deals with the fluorescent contribution\(^3\).

### 2.5.2. Whiteness

Brightness has been set as a standard in the paper industry to keep track of the bleaching process since the 1930s. However, brightness cannot describe true color of a paper sheet. Unlike brightness, the whiteness of paper can be properly specified by its red and green as well as blue reflectance values\(^82,83\).

Whiteness is a color measurement which measures reflectance across all wavelengths in the visible light spectrum (380-780 nm) and provides a better idea about papers' color reproduction capability. The measurement of whiteness matches what the human eye perceives\(^81\).

A whiteness index has been used in the industry because a single number is easier to understand and communicate, than a spectral curve. The paper industry uses several different systems to describe color and optical properties of paper, which include CIE, Hunter, and Ganz whiteness\(^3,83\).
The ASTM/CIE Whiteness formulation\textsuperscript{84} was analyzed on slightly colored papers\textsuperscript{83,85} and is given by:

\[
\text{ASTM/CIE whiteness} = Y + 800 \cdot (x_n - x) + 1700 \cdot (y_n - y) \tag{9}
\]

\[
x = X / (X+Y+Z), \quad y = Y / (X+Y+Z)
\]

Where \(x_n = 0.3138\), and \(y_n = 0.3310\) for \(D_65/10^\circ\).

\[
\text{ASTM/CIE tint} = 1000 \cdot (x_n - x) - 650 \cdot (y_n - y)
\]

Positive tint indicates greenishness.

Negative tint indicates reddishness.

This equation can be used only in a limited region. The values of \(W\) fall within the limits given by:

\[
5Y-280 > \text{CIE whiteness} > 40
\]

And the tint relation for \(10^\circ\)

\[
3 > 900 \cdot (x_n - x) - 650 \cdot (y_n - y) > -3
\]

One disadvantage in CIE whiteness is that this equation does not clarify whether the whiteness has any component of bluishness or yellowishness. The ASTM standard Test Method E313 measuring for yellowness is given by the equation as follows:

\[
YI = 100 \cdot (C_xX - C_zZ) / Y \tag{10}
\]

Where \(C_x = 1.301\) and \(C_z = 1.150\) for \(D_65/10^\circ\);

\(C_x = 1.277\) and \(C_z = 1.059\) for \(C/2^\circ\).

Equation for Hunter Whiteness:

\[
\text{Hunter WI} = L - 3b \tag{11}
\]

Where \(L\) and \(b\) are Hunter values

Equation for Ganz Whiteness:

\[
W_{\text{Ganz}} = Y + 1869.3 \cdot (x_n - x) + 3695.2 \cdot (y_n - y) \tag{12}
\]

\[
x = X / (X+Y+Z), \quad y = Y / (X+Y+Z)
\]
Where $x_n = 0.3138$, and $y_n = 0.3310$ for $D_{65}/10^\circ$.

2.5.3. Opacity

Opacity is a measure of a paper’s ability to block the passage of light. When light illuminates on a paper surface, some portions will be reflected, some portions will be absorbed, and the remaining portions will be transmitted through the paper. The light transmittance determines the degree of opacity.

Opacity is of particular interest for papers that are to be printed on both sides, such as in books and magazines. Sufficient opacity is important to prevent printed text from showing through. Too much show-through of printed images can reduce print contrast and have influence on visual appearance of the printed image. The degree of opacity is affected by several factors, such as paper sizing, paper coating, basis weight, bulk level, degree of refining, calendering, etc. For example, the addition of fillers can increase the number of interfaces and therefore increase the opacity. The degree of refining increases the fiber bonding, however, it reduces the number of fiber-air interfaces and thus reduces the opacity.

The opacity of papers uses 0-100% contrast ratio scale for paper measurement. Opacity with 0% represents transparent, while opacity with 100% is considered as opaque. Groundwood and unbleached fibers have greater light absorption, so that good opacity can be obtained. There are two commonly used methods determine opacity: TAPPI opacity and ISO opacity (Printing opacity). The only differences in measuring techniques are in the nature of the backing.
2.5.3.1. TAPPI Opacity

The TAPPI opacity geometry employs a 15° illumination/diffused viewing (15°/d) and a paper opacity measurement called Contrast Ratio has been used:

TAPPI Opacity (89% reflectance backing), % = \( \frac{R_0}{R_{0.89}} \times 100 \)

Where \( R_0 \) is the reflectance factor measured against a black backing under standard conditions; \( R_{0.89} \) is the reflectance factor of the same sheet measured against a backing with a reflectance of 0.89 or 89%.

In the TAPPI method, the first reflectance measurement is made for a single sheet of paper held against a matt black background. The second reading is made against a white background provided by a standard ceramic tile\(^{19,80}\).

2.5.3.2. ISO Opacity

The geometry employed by ISO opacity is the same as that for diffuse brightness (d/0°). The diffuse opacity method uses a thick stack of the paper instead\(^9\).

ISO or printing opacity, % = \( \frac{R_0}{R_-} \times 100 \)

Where \( R_0 \) is the reflectance of a single sheet with a black backing, \( R_- \) is the reflectance of a single sheet having a backing of multiple sheets.

In the ISO method, the first reflectance measurement is also made for a single sheet of paper held against a matt black background. The second measurement is made against a pad of the same paper, thick enough to prevent transmission. The opacity of a completely opaque paper is 100%. The opacity of printing paper is usually at least 80%. Although the printing opacity method provides more accurate measures,
the TAPPI opacity method (contrast ratio) is generally used because of its speed and convenience\textsuperscript{3, 19}.

2.5.4. Gloss

Gloss is the attribute of a paper surface that makes the images look shiny or lustrous. When light strikes on a flat surface of a sheet of paper, it is reflected primarily as parallel rays, resulting in specular reflection (the angle of reflection is the same as the angle of incidence). The amount of specular reflection is dependent upon the optical smoothness of the surface\textsuperscript{3, 6, 19}.

Paper gloss has influence on the color of a print, due to it affects the way light is reflected through the ink. In order to remain uniform color printing throughout a job, the variations in gloss must be monitored and kept to a minimum level. Paper gloss is expressed as a ratio of reflected to incident light in the specular direction. A gloss meter uses a photocell to measure the relative amount of incident light that is reflected from a paper sample. Glossmeters vary in geometry. For evaluation of high-gloss papers and boards such as lacquered and cast-coated papers, a 20° method (TAPPI T 653) is usually used. For the majority of papers there is a greater degree of diffuse reflectance. The paper industry has adopted a 75° specular gloss method (TAPPI T 480) to measure gloss for this kind of paper\textsuperscript{19, 80}.

The print gloss is obtained after the application of ink, usually in solid patches. It is affected by the paper surface gloss and the ink absorption. Both the color appearance and its intensity will change along with ink penetration. Printed papers having high gloss can provide good color saturation, whereas printed papers with low gloss will have a dull
unsaturated appearance. In most situations, papers required to carry multicolor printing need a high gloss is required to give intensity or color saturation. Print gloss is generally based on a 60° specular gloss method. Thus, when comparing print gloss with paper gloss the comparison should be done with the same angles (hopefully the same instruments).

Glossy papers usually associate gloss with high surface smoothness and good printing quality. High quality printed images also come up with high gloss by increasing print gloss. However, high gloss is often associated with poor reading quality due to glare. Gloss can be reduced by coating paper with highly opaque pigments.

2.6. Ink-paper Interactions

Paper is a porous material. When printing inks are applied onto the paper surface, they wet the surface and penetrate into pores by capillary pressure. The ink-paper interaction determines the ink absorption and print quality. A paper surface with a high energy surface is highly wettable by water and inks.

Contact angle is one of methods for assessing absorbency of paper and wettability, which is measured from the solid-liquid interface and through the liquid to the tangent drawn at the solid-liquid interface (Figure 6). Contact angles of 0° to 90° represent wetting, whereas from 90° to 180° represent nonwetting. A contact angle of 90° represents partial wetting. Contact angles can be measured by recording an image using a digital camera and measuring the tangential values of θ. A First Ten Angstroms (FTA) with FTA 32 Video 2.0 software is a dynamic video capture unit that allows for precise timing of the captured image after the ink is applied to the substrate.
Figure 6. The relationship between the three interfacial tensions ($\gamma_{sl}$: solid-liquid; $\gamma_{lv}$: liquid-vapor; $\gamma_{sv}$: solid-vapor) and contact angle $\theta$.  

The Emco Dynamic Penetration Tester DPM, equipped with DPM software version 3.31 is another tool to measure the absorption or wetting characteristics of paper samples. The Emco DPM works by sending ultrasonic pulses through a fluid medium, where paper has been submerged, and based on how long the ultrasonic pulses would take to reach its respective receiver. The results are displayed in graphical form as a transmission versus time.

### 2.7. Print Attributes

Print quality is associated with a number of variables in all printing process including paper, inks, and the press itself. The attributes dealing with print quality include density, color saturation, and surface uniformity. In this research, print attributes are defined in terms of optical density, print mottle, and color gamut.

#### 2.7.1. Optical Density

In the printing industry, density usually refers to the ability of a print to absorb light. Generally, the darker a process color is to the eye, the higher the density. The optimum solid ink density will give the highest contrast without flattening the shadow contrast. Decreasing solid ink density may decrease mid-tone dot gain, but will affect shadows more.
and will weaken the saturated and overall print colors. With poorer quality of paper, a lower solid ink density may result. Density is measured with a densitometer. Reflective density is the ratio of how much light is incident on the paper compared to how much reflects back, that is:

\[ D = \log \frac{I_i}{I_r} \]  

Where \( D \) is reflective density; \( I_i \) is intensity of reflected light; \( I_r \) is the intensity of reflected light.

2.7.2. Print Mottle

Mottling is the term for non-uniform appearance of prints. An uneven absorption of the inks by the paper between the printing units of a multicolor press leads to uneven re-splitting on the subsequent blankets. Unevenness in absorption causes uneven ink acceptance, resulting in visible, particularly in overprinting with potentially increased severity of the mottling effects. Mottling is influenced significantly by the characteristics of the paper with regard to the homogeneity of its structure and its coating. Variation in the density, surface smoothness, fiber content, fines, filler content, sizing surface, as well as specific energy of the paper, can have a dramatic influence on the ability of an ink to transfer to the surface.

2.7.3. Color Gamut

Color gamut is a significant quality factors for either the printing processes or digital proofing systems. The color gamut is the range of colors that a particular combination of printer, ink, media, and RIP can achieve. Each device has a fixed range of colors and tone that it can
reproduce. The gamut of the printer is affected by the substrate properties. Color gamut is used as a measure of color reproduction capability of a device, and is often used to compare different color reproduction devices or ink sets and their performance.

Color gamut mapping is the main function in color management to maintain the color appearance of an original. In order to obtain accurate color matching between devices, the color gamut boundary needs to be well defined. Color Gamut Boundary (CGB) refers to a surface determined by a color gamut's extremes. The color gamut surface provides important information for gamut volume calculation and gamut mapping across the different color media. In recent years, several different methods have been developed to calculate the gamut surface. Based on the color gamut boundary, the color gamut surface has been defined and from these the color gamut volume is calculated. The characterization of substrates based on differences in gamut boundaries and volume is a new way the color gamut can be incorporated into printing production.

When all of the colors in a color gamut are plotted in a three dimensional coordinate system they will form a color solid. The volume of the solid would be proportional to the effective number of colors in the gamut. Color gamut of a given printing system is evaluated in terms of gamut volume, which can be interpreted as the number of independent colors that can be printed on the designated substrate within a ΔE tolerance of \( \sqrt{3} \) (i.e. the diagonal of a unit cube). Volume is then expressed in cubic CIELAB units (cCu). Higher volumes indicate the possibility of making more color combinations. Therefore, color gamut can be treated as an indicator predicting color reproduction capability of a device. Recently,
gamut volume with a given printing device has been proposed as a measure of the quality of paper and its coating."
CHAPTER 3

PROBLEM STATEMENT

There is no doubt that paper physical properties have significant effects on image reproduction for either printing or proofing processes. The completeness of the image transfer, the uniformity of ink absorbency, and color density are greatly influenced by the paper surface and physical properties. The optical properties of a paper influence the visual quality of the printed image and contribute more than any other factors to its appearance. Therefore, it is necessary to understand how these paper properties affect print quality and color reproduction for gravure publication printing.

The effects of paper properties on print quality and color reproduction capability were discussed. The overall aim of this research is to come up with the paper properties that affect the color reproduction and color the most. This research is aimed to perform the following tasks:

**Task 1:** Evaluate the influence of coating formulations on paper properties, as well as the impact of the paper properties on print quality for gravure light weight coated paper (LWC) and ink-jet glossy paper. The type of latex used in the coating formulation will affect the strength and absorbency characteristics of the coated paper. Different types of latex polymers were considered in the LWC coating formulations to evaluate their influence on final paper properties and print quality. Coated ink-jet media are necessary to produce the desired glossy image characteristics and provide good color reproduction capability. The performance of the fumed alumina and fumed silica ink-jet coatings were examined in terms of roughness, paper gloss, optical density and color gamut.
Task 2: Study the paper properties and their relationship to print attributes, including examining the correlation between gamut volume and the paper surface/physical/optical properties and their relationship to color gamut in the digital proofing system. Both gravure publication printing substrates and manufacturer recommend proofing papers were tested.

Task 3: Investigate the proof-press color matching capability of inkjet digital printers by evaluating color difference ($\Delta E_{2000}^*$), paper white simulation, and process consistency. The accuracy of proof-press color matching is affected by the printer, software and substrate involved in digital proofing processes. Therefore, the best print combination to obtain good proof-press color matching for gravure publication printing was recommended.

Task 4: Examine the quality of spot color reproduction with an inkjet printer, and establish a digital proofing solution for spot color reproduction of gravure product printing. Several typical spot colors used in product gravure printing, in particular for decorative laminates, were used as matching targets. Different proofing systems were tested. Color gamuts of print combinations were compared and the quality of spot color reproduction was evaluated in terms of the $\Delta E_{ab}^*$ in $L^*a^*b^*$ color space for selected spot colors.
CHAPTER 4

EXPERIMENTAL

Paper is a crucial variable in a printing reproduction process. Dealing with print quality of images, paper properties need to be well defined and controlled. This study investigates the influence of coating formulations on the paper and print quality for the gravure publication printing and ink-jet digital printing. Since ink-jet digital proofing became an important step in the gravure printing process, the effect of paper properties on the color reproduction was examined, as well as color reproduction capability with ink-jet proofing systems was evaluated in terms of proof-press color matching and spot color reproduction capability.

4.1. Coating Formulations

The application of coating is for the purposes of covering the fibers and voids to improve paper properties, improving the print quality by holding the ink on the surface of the paper, and creating a detailed uniform printed image. This research designed coating formulations for gravure LWC paper and ink-jet glossy paper.

4.1.1. Coating Formulations for LWC Paper

A styrene-butadiene (SB) and several styrene butadiene acrylonitrile (SBA) latexes were used in this study. Latex polymers were formulated into a pigment system consisted of 80 parts delaminated clay and 20 parts of No. 1 clay, using 6 parts latex based on pigment and 0.1 part disperser (Dispex N40) with RM 232 thickener. Each latex was
evaluated as the sole binder in the coating formulation which was applied to the base paper of 44.82 g/m² basis weight.

4.1.2. Coating Formulations for Ink-jet Paper

Commercial pigment samples of cationic silica (Cabot 022) and fumed alumina (Cabot 003) were used. Celvol 103 fully hydrolyzed polyvinyl alcohol (PVOH) and polyvinyl pyrrolidone (PVP) were used as binders. Formulations were prepared using a 4:1 pigment: binder ratio.

4.2. Substrates

In order to study the paper properties and their relationship to print attributes in the digital proofing system, three gravure publication printing substrates—free sheet coated paper, light weight coated paper, and newsprint—were selected as the actual production printing substrates. Furthermore, three types of manufacturer recommended proofing papers—semimatte photo paper, pearl proof paper, and selected proof paper—were tested and compared. For the spot color reproduction, actual production printing substrates used in gravure product printing were also included for testing. Table 3 provides basic information of substrates used in this study.

4.3. Printing Procedures

4.3.1. Gravure Printing

The coated LWC papers were printed on a rotogravure web press Model 118 from Cerutti Group (Italy), located at the Western Michigan University (WMU) Printing Pilot Plant. Commercial toluene-based coated yellow, magenta, cyan and black inks for rotogravure from Flint Group were used. The ink efflux time with Shell cup #2 was kept at 22 ± 0.5
Table 3. Selected properties of tested substrates

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Basis Weight [g/m²]</th>
<th>Caliper [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>Gravure Publication Printing Substrates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free Sheet</td>
<td>67.7</td>
<td>0.6</td>
</tr>
<tr>
<td>LWC</td>
<td>50.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Newsprint</td>
<td>49.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Gravure Product Printing Substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual Production Printing Substrate</td>
<td>30.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Manufacturer Recommended Proofing Papers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semimatte Photo Paper</td>
<td>255.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Pearl Proof Paper</td>
<td>237.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Selected Proof Paper</td>
<td>192.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

seconds for yellow and magenta, 25 ± 0.5 seconds for cyan, and 20 ± 0.5 seconds for black ink. Printing was done at 600 ft/min with electrostatic assist (ESA) on. The target print densities were 1.00 for yellow, 1.35 for magenta, 1.35 for cyan, and 1.50 for black, which was achieved for the first printed substrate, and then the same printing condition was maintained during the printing process of the rest of the substrates. Other gravure publication grades such as free sheet and newsprint were printed in the same printing condition, serving as references for print quality comparison and targets for proof-press color matching.

4.3.2. Ink-jet Printing

Ink-jet coating samples were printed on two different printers: an Epson Stylus Pro 4000 printer with UltraChrome pigmented inks and a Canon PIXMA Pro 9000 printer with dye-based inks. Although the UltraChrome ink set in the Epson printer lacks the extended Red and Green inks that are found in the Canon printer, the previous testing showed that both printers can yield very similar gamut sizes on
commercially available glossy substrates\textsuperscript{104}. It was confirmed in order to continue with the color gamut assessments on investigated glossy coatings. ICC profiles were generated for these coated papers. A 6" x 8" RGB chart was printed on the coated sheets without any ink limitation. Those printed charts were then measured with an X-Rite DTP70 and the ICC profiles were generated by using MonacoProfiler software.

4.4. Paper Properties Testing

The key properties evaluated included surface properties such as roughness, formation index, pore size, porosity, and air permeability coefficient. The instruments used for paper properties measurement were summarized in Table 4.

<table>
<thead>
<tr>
<th>Paper Properties</th>
<th>Measuring Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emveco Roughness [μm]</td>
<td>EMVECO stylus profilometer</td>
</tr>
<tr>
<td>PPS Roughness [μm]</td>
<td>Parker Print-Surf tester (Model 90)</td>
</tr>
<tr>
<td>Formation Index</td>
<td>M/K system formation tester</td>
</tr>
<tr>
<td>Pore Size [nm]</td>
<td>Mercury intrusion porosimetry</td>
</tr>
<tr>
<td>Porosity [%]</td>
<td>Mercury intrusion porosimetry</td>
</tr>
<tr>
<td>Air Permeability Coefficient [μm²]</td>
<td>Parker Print-Surf (PPS) tester Using equation of $K = 0.048838 \times Q \times X$ Q=PPS Porosity; X=thickness</td>
</tr>
<tr>
<td>Brightness [%]</td>
<td>Brightimeter MICRO S-5 (C/2°)</td>
</tr>
<tr>
<td>Whiteness</td>
<td>Brightimeter MICRO S-5 (ASTM standard, C/2°)</td>
</tr>
<tr>
<td>Opacity [%]</td>
<td>BNL-2 Opacimeter (TAPPI Standard)</td>
</tr>
<tr>
<td>Paper Gloss [%]</td>
<td>Novo-Gloss™ Glossmeter</td>
</tr>
</tbody>
</table>

A Parker Print-Surf Model 90 was used at pressures of 1000 kPa with hard backing. An Electronic Microgage Model 210-R (Emveco, Inc) with the spherical steel stylus having a radius of 0.001 inch was used for profilometer measurement. The test conditions were 500 readings per
group, 3 groups, 0.1 mm reading space, and 0.5 mm/s scanning speed. The roughness $R$ was then calculated using $^{86}$:

$$R = \frac{1}{499} \sum_{i=1}^{499} |X_{i+1} - X_i|, \quad i = 1, 2, \ldots, 499$$ (14)

An M/K system formation tester was employed to obtain formation index values, which are determined by variations in light transmitted through the tested sheet as the light source scans across the sheet rapidly. Each measurement is amplified and stored in one of 64 optically measured "basis weight" classes or memory bins. The greater the deviation in optical density from the instantaneous average, the further away a given data point is stored from the central bin or average weight class of the histogram. At the end of each scan, the number of contiguous bins and the amplitude or peak heights of the histogram were recorded. The more uniform a sheet, the greater its peak height is, and the fewer the number of bins into which the data fall. In other words, the larger the formation index, the more uniform the sheet. The formation index was calculated based on the equation of $^{105}$:

$$\text{Formation Index} = \frac{\text{Peak Height}}{\text{No. of Bins}} \times \frac{1}{100}$$ (15)

An Autopore IV 9500 mercury porosimeter, measuring the incremental increase of volume penetrated as the pressure rises, was employed for the porosity-related characteristic measurements, such as of pore size, volume, and distribution of a paper. The pressure required to intrude mercury into the sample's pores is inversely proportional to the size of the pores. Paper samples were placed in a penetrometer and evacuated at 50 $\mu$m Hg$^{79, 106, 107, 108}$.

The permeability of each substrate was calculated from the Parker Print Surf porosity value and its thickness using the Pal's equation$^{76}$. 

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4. 5. Printing Properties Testing

Printed paper samples were collected and their printing properties were evaluated in terms of dynamic penetration test, contact angle (wetting property), optical density, print gloss, print mottle (ink uniformity), and color capability (color gamut).

The absorption characteristics of LWC paper samples were measured using Emco Dynamic Penetration Measurement (DPM), which is equipped with DPM software version 3.31. Contact angles were measured on the LWC coated paper samples during contact times from 0 to 2.5s, with a contact angle measurement apparatus (FTA 200, First Ten Ångstroms). The contact angle goniometer is equipped with a horizontally aligned microscope and digital high speed camera to capture the evolution of the drop-surface interaction. Further insights into the interactions between liquid and paper surfaces are demonstrated in terms of the dispersive and polar energy contributions in the equation of Owens and Wendt. DI water and hexadecane were used as the characterization liquids. The surface tensions of these liquids are listed in Table 5.

Table 5. Surface tensions for water and hexadecane (mJ/m²)

<table>
<thead>
<tr>
<th>Liquid</th>
<th>(\gamma_L)</th>
<th>(\gamma_L^D)</th>
<th>(\gamma_L^P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>72.8</td>
<td>21.8</td>
<td>51.0</td>
</tr>
<tr>
<td>Hexadecane</td>
<td>27.1</td>
<td>27.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Note: \(\gamma_L\) = surface tension of the liquids. \(\gamma_L^D\) = dispersive component of the surface tension of the liquids. \(\gamma_L^P\) = polar component of the surface tension of the liquids.

The polar and dispersive components of the paper surface energy were estimated from the contact angle measurements using Owens and Wendt equation.
\[
\frac{y_L(1+\cos \theta)}{2\sqrt{y_P}} = \sqrt{y_S^D \left(\frac{\sqrt{y_L}}{\sqrt{y_P}}\right)} + \sqrt{y_S^P} 
\]

where \(y_S\) represents the surface energy of the solid. \(y_S^D\) represents the dispersive component of the surface energy of the solid. \(y_S^P\) represents the polar component of the surface energy of the solid. The paper surface free energy can be expressed as the sum of the dispersive \(y_S^D\) and the polar \(y_S^P\) component of \(y_S\), as follows:

\[
y_S = y_S^D + y_S^P
\]

Paper gloss at 75° and print gloss at 60° were measured using a Novo-Gloss™ Glossmeter. Print mottle was evaluated with Verity IA Color Image Analysis software by analyzing scanned solid CMYK patches. The print mottle measurement algorithm is derivative of the Verity IA stochastic frequency distribution analysis\(^{114}\). The ECI2002R CMYK test target designed for the DTP 70 spectrophotometer was used to generate ICC profiles. The patches of this target chart are specially designed to produce a good distribution of colors in \(L^*a^*b^*\) space. The color reproduction capability (color gamut) was evaluated in terms of gamut volume. Table 6 lists the instruments/software used for printing properties/color reproduction capability measurement.

4.6. Proof-press Color Matching

Digital proofing needs to predict how the print is going to look on press. The accuracy of proof-press color matching is affected by the printer, software and substrate involved in digital proofing processes. This trial investigates the color matching capability of digital printers for the gravure publication grade papers. The equipment/materials and color management tools used in this trial are shown in Table 7.
Table 6. Instruments used for printing properties/color reproduction capability measurement

<table>
<thead>
<tr>
<th>Printing Properties</th>
<th>Measuring Instrument/Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Penetration Test</td>
<td>Emco Dynamic Penetration Measurement (DPM)</td>
</tr>
<tr>
<td></td>
<td>Measuring area: 10mm-diameter</td>
</tr>
<tr>
<td>Contact Angle Test</td>
<td>FTA 200, First Ten Ångstroms</td>
</tr>
<tr>
<td>Paper Gloss</td>
<td>Novo-Gloss™ Glossmeter (at 75°)</td>
</tr>
<tr>
<td>Print Gloss</td>
<td>Novo-Gloss™ Glossmeter (at 60°)</td>
</tr>
<tr>
<td>Verity Print Mottle</td>
<td>Verity IA Color Image Analysis software (equipped with a scanner)</td>
</tr>
<tr>
<td>Color Gamut (Gamut Volume)</td>
<td>Target: ECI 2002R</td>
</tr>
<tr>
<td></td>
<td>Measuring Tool: X-Rite DTP70 Spectrophotometer</td>
</tr>
<tr>
<td></td>
<td>Profiling Software: X-Rite MonacoPROFILER 4.8</td>
</tr>
<tr>
<td></td>
<td>Gamut Evaluation Software: CHROMiX ColorThink 3.0 Pro</td>
</tr>
</tbody>
</table>

Table 7. Equipment and materials used for proof-press color matching

<table>
<thead>
<tr>
<th>Equipment and Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Printing</td>
</tr>
<tr>
<td>♦ Epson Stylus Pro 4000 with UltraChrome pigmented inks</td>
</tr>
<tr>
<td>♦ Epson Stylus Pro 9800 with UltraChrome K3 inks</td>
</tr>
<tr>
<td>Matching Targets</td>
</tr>
<tr>
<td>♦ Free sheet coated paper (FS)</td>
</tr>
<tr>
<td>♦ Light weight coated paper (LWC)</td>
</tr>
<tr>
<td>♦ Newsprint (News)</td>
</tr>
<tr>
<td>Proofing Papers</td>
</tr>
<tr>
<td>♦ Semimatte Photo Paper (PSPP)</td>
</tr>
<tr>
<td>♦ Pearl Proof Paper (Pearl)</td>
</tr>
<tr>
<td>♦ Selected Proof Paper (Selected)</td>
</tr>
<tr>
<td>RIP</td>
</tr>
<tr>
<td>♦ GMG ColorProof RIP</td>
</tr>
<tr>
<td>Color Matching Test Chart</td>
</tr>
<tr>
<td>♦ ECI2002R CMYK Test Target</td>
</tr>
<tr>
<td>Measuring Device</td>
</tr>
<tr>
<td>♦ X-Rite DTP 70 Spectrophotometer</td>
</tr>
</tbody>
</table>

4.7. Spot Color Reproduction with Ink-jet Printers

Spot color is widely used in commercial, product or packaging printing to obtain a colorful appearance. This trial tests the ability of ink-jet for reproducing spot colors used in gravure product printing. The equipment/materials and color management tools used in spot color reproduction testing are shown in Table 8.
4.8. Data Analysis

The effect of paper properties on the print quality for the gravure publication printing, together with color reproduction capability with ink-jet proofing systems was evaluated. SPSS 12 and Minitab 14 statistical software packages were used for data analyses. The following analyses were performed:

- **Correlation Analysis**: Pearson's correlation coefficient was used to measure association between paper surface properties and printing properties/color reproduction capability for the gravure publication printing. Furthermore, understanding the relationship between paper properties and color gamut can help to predict and control color gamut in the digital proofing system. The relationships between paper properties and color gamut (gamut volume) were also investigated.

- **Process Capability Analysis**: the color matching capability of ink-jet digital proofing systems was evaluated in terms of color difference
(ΔE*2000) and process consistency. For the purpose of investigation of the process capability of digital color proofing systems when matching proof to press, the tools used to analyze the consistency are Individual Control Chart (I Chart), Moving Range Charts (MR Chart), and Capability Analysis. The Process capability ratio (PCR or Cp index) based on color difference (ΔE*2000) was determined statistically.

- Color reproduction capability: the quality of color reproduction capability was evaluated in terms of the ΔE in L*a*b* color space. The color gamuts and gamut volume of tested print combinations were compared using CHROMiX ColorThink 3 Pro software.
CHAPTER 5

RESULTS AND DISCUSSION

5.1. The Influence of Coating on the Paper and Printing Properties of LWC Paper

This trial evaluated the influence of seven different latex polymers on paper properties and then the impact of the paper properties on printing properties and color reproduction capability. The correlations between paper surface properties and printing properties/color reproduction capability were investigated.

5.1.1. The Design of Coating Formulations for LWC Paper

Styrene-butadiene (SB) and styrene butadiene acrylonitrile (SBA) latexes were used in this study. Latexes used in this research were chosen from commercially available latex products. Some key characteristics of the latexes selected for this paper are listed in Table 9. Coating formulations are shown in Table 10.

Table 9. Key characteristics of latexes

<table>
<thead>
<tr>
<th>Latex</th>
<th>Chemistry</th>
<th>Particle Size</th>
<th>Degree of carboxylation</th>
<th>Tg (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latex A</td>
<td>styrene butadiene (SB)</td>
<td>Large</td>
<td>Low</td>
<td>-28</td>
</tr>
<tr>
<td>Latex B</td>
<td>styrene butadiene acrylonitrile (SBA)</td>
<td>Large</td>
<td>Low</td>
<td>-2</td>
</tr>
<tr>
<td>Latex C</td>
<td>styrene butadiene acrylonitrile (SBA)</td>
<td>Large</td>
<td>Low</td>
<td>-25</td>
</tr>
<tr>
<td>Latex D</td>
<td>styrene butadiene acrylonitrile (SBA)</td>
<td>Medium</td>
<td>Low</td>
<td>10</td>
</tr>
<tr>
<td>Latex E</td>
<td>styrene butadiene acrylonitrile (SBA)</td>
<td>Medium</td>
<td>Low</td>
<td>-15</td>
</tr>
<tr>
<td>Latex F</td>
<td>styrene butadiene acrylonitrile (SBA)</td>
<td>Medium</td>
<td>Low</td>
<td>-6</td>
</tr>
<tr>
<td>Latex G</td>
<td>styrene butadiene acrylonitrile (SBA)</td>
<td>Medium-Large</td>
<td>Low</td>
<td>-6</td>
</tr>
</tbody>
</table>
Table 10. Coating formulations (added amount: parts per hundred, pph)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Pigment</th>
<th>Latex A</th>
<th>Latex B</th>
<th>Latex C</th>
<th>Latex D</th>
<th>Latex E</th>
<th>Latex F</th>
<th>Latex G</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delaminated clay, Astraplate</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>No. 1 clay, KCS</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Latex polymer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latex A</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latex B</td>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latex C</td>
<td></td>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latex D</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latex E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latex F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Latex G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickener</th>
<th>RM 232</th>
<th>✓</th>
<th>✓</th>
<th>✓</th>
<th>✓</th>
<th>✓</th>
<th>✓</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disperser</td>
<td>Dispex N40</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

5.1.2. LWC Paper Properties

Table 11 summarizes paper properties testing results. It is seen that roughness is one of the most important factors affecting print quality. The average roughness readings for the tested samples are in the range of 1.3 to 1.6 micron. At the same time, sample 1 with latex A has a smoother surface, while sample 4 with latex D has a rougher surface than the rest of the papers. The porosity of a paper determines ink setting speed and uniformity. The highest percent porosity was found in the sample 2 with 65.0%. Sample 6 has the lowest percent porosity at 56.5%. The average pore size readings for the tested samples are in the range of 180 to 240 nm. Sample 2 with latex B tends to have a larger pore size, while sample 1 with latex A has a smaller pore size.
Table 11. Paper properties measurement

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
<td>Mean</td>
<td>Std. Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>1</td>
<td>1.38</td>
<td>0.06</td>
<td>203.0</td>
<td>59.8</td>
<td>10.6x10⁻⁶</td>
</tr>
<tr>
<td>2</td>
<td>1.58</td>
<td>0.07</td>
<td>239.2</td>
<td>65.0</td>
<td>21.3x10⁻⁶</td>
</tr>
<tr>
<td>3</td>
<td>1.59</td>
<td>0.08</td>
<td>204.2</td>
<td>63.4</td>
<td>22.8x10⁻⁶</td>
</tr>
<tr>
<td>4</td>
<td>1.60</td>
<td>0.06</td>
<td>232.7</td>
<td>64.1</td>
<td>24.9x10⁻⁶</td>
</tr>
<tr>
<td>5</td>
<td>1.51</td>
<td>0.06</td>
<td>208.8</td>
<td>62.1</td>
<td>19.3x10⁻⁶</td>
</tr>
<tr>
<td>6</td>
<td>1.58</td>
<td>0.06</td>
<td>188.6</td>
<td>56.5</td>
<td>23.4x10⁻⁶</td>
</tr>
<tr>
<td>7</td>
<td>1.54</td>
<td>0.07</td>
<td>231.6</td>
<td>60.9</td>
<td>21.6x10⁻⁶</td>
</tr>
</tbody>
</table>

Optical Properties

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>TAPPI Brightness [%]</th>
<th>TAPPI Opacity [%]</th>
<th>Paper gloss at 75° [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>1</td>
<td>69.9</td>
<td>0.1</td>
<td>82.0</td>
</tr>
<tr>
<td>2</td>
<td>70.6</td>
<td>0.2</td>
<td>82.5</td>
</tr>
<tr>
<td>3</td>
<td>70.6</td>
<td>0.2</td>
<td>82.5</td>
</tr>
<tr>
<td>4</td>
<td>70.4</td>
<td>0.3</td>
<td>82.7</td>
</tr>
<tr>
<td>5</td>
<td>70.5</td>
<td>0.1</td>
<td>82.1</td>
</tr>
<tr>
<td>6</td>
<td>70.4</td>
<td>0.3</td>
<td>82.2</td>
</tr>
<tr>
<td>7</td>
<td>70.8</td>
<td>0.6</td>
<td>82.3</td>
</tr>
</tbody>
</table>

The pore size distributions of all tested paper samples are shown in Figure 7. All tested paper samples have peaks of pore sizes between 100 to 10,000 nm. The pore sizes over 10,000 nm (not shown) were not considered, since they originate from raw stock porosity and possible artifacts. Air permeability, a porosity-related characteristic, is the property of a paper that allows air to flow through it under a pressure difference across the thickness of the sheet. Table 11 shows that sample 1 has the lowest air permeability coefficient value of 10.6 x 10⁻⁶ μm² and the smallest standard deviation value, while sample 4 has the highest air permeability coefficient value of 24.9 x 10⁻⁶ μm² and largest standard deviation value. In other words, less air flows through sample 1.
Table 11 shows that sample 4 with latex D is more uniform than other tested samples. As shown in Table 11, the average brightness readings for the tested paper samples are in the range of 69 to 71%. Sample 7 with latex G is slightly brighter than other tested samples. The average opacity readings for the tested paper samples are in the range of 81 to 83%. Sample 5 with latex E has the highest paper gloss of 50.6%, while sample 3 with latex C has the lowest paper gloss of 44.1%.

5.1.3. Printing Properties

5.1.3.1. Emco Dynamic Penetration Test

The Emco dynamic penetration test can be considered as an indicator to predict ink-paper interactions. In this study, paper samples were printed using toluene-based ink. Both deionized water (DI water) and toluene served as testing liquids at 23°C. The dynamics of DI
water/toluene and tested paper sample interactions are illustrated in Figure 8.

![Figure 8. Water penetration characteristics of tested samples](image)

There are obvious differences between a water ultrasound curve and a toluene ultrasound curve. It shows that all paper samples absorbed more DI water (dashed-line) than toluene (solid-line) after one second. In the case of treating with toluene fluid, the fastest penetration was found in sample 2 (magenta solid-line), while sample 1 (cyan solid-line) absorbs the least amount of toluene during the whole 5 seconds of measurement interval. It is interesting to note that toluene somehow swells the structure of sample 1 (cyan solid-line) between 0.5 to 3.0 seconds. Possible reason for this is that the interaction occurs between toluene and the coating layer, resulting in impregnating the structure. In terms of DI water fluid, all tested paper samples absorbed water immediately (within 3.5 seconds) after they came into the contact with water and tend to have similar absorption curves. The slowest penetration was also found in the sample 1
Sample 1 has relatively low air permeability and smaller average pore size, which correlates with its slower fluid penetration rate.

5.1.3.2. Wetting Property Test

The wetting properties of LWC paper samples were evaluated in terms of contact angle, which is one of methods for assessing absorbency of paper. Figure 9 shows changes of DI water contact angle with time for the coated paper samples. The contact angles decreased with time because of spreading. The most rapid changes in the contact angle values happened within the first 0.5-0.7 seconds. It shows that the sample 4 is more hydrophilic than the other samples.

![Figure 9. Contact angles with time in 2.5 s interval](image)

The contact angle measurement on paper is influenced by liquid penetration into paper as well as liquid spreading on paper surface. The measured contact angle is highly dependent on surface roughness, porosity of paper, and spreading resistance of fiber edges. Table 12 shows contact angle changes of water on each tested paper sample. The
initial contact angles of samples are in the range of 67° to 75°, after 2.5 seconds, the contact angles decreased to about 62°. Sample 1, 5, and 7 are smoother and the water drop is prone to spread less onto paper.

Table 12. Results of contact angle measurement of tested paper samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Initial contact angle [°]</th>
<th>Contact angle at 2.5 s [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67.08</td>
<td>61.53</td>
</tr>
<tr>
<td>2</td>
<td>69.21</td>
<td>62.42</td>
</tr>
<tr>
<td>3</td>
<td>72.21</td>
<td>58.84</td>
</tr>
<tr>
<td>4</td>
<td>70.58</td>
<td>57.37</td>
</tr>
<tr>
<td>5</td>
<td>74.29</td>
<td>62.34</td>
</tr>
<tr>
<td>6</td>
<td>69.18</td>
<td>62.98</td>
</tr>
<tr>
<td>7</td>
<td>71.48</td>
<td>62.52</td>
</tr>
</tbody>
</table>

The characterization liquids’ contact angles and surface energies for the tested paper samples are listed in Table 13. The total surface energies of samples 1 to 7 are in the range of 42-46 mJ/m². Such increased polar component surface energy could explain why sample 4 is better wetted by water than other paper samples. For all paper samples, sample 4 tends to have higher surface energy, which agrees with Figure 8.

Table 13. Surface energies of paper samples as derived from contact angle measurements

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Water contact angle (°)</th>
<th>Hexadecane contact angle (°)</th>
<th>Dispersive component surface energy (mJ/m²)</th>
<th>Polar component surface energy (mJ/m²)</th>
<th>Total surface energy (mJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>517</td>
<td>62.19</td>
<td>5.54</td>
<td>26.97 ± 0.01</td>
<td>16.64 ± 0.13</td>
<td>43.61 ± 0.13</td>
</tr>
<tr>
<td>518</td>
<td>62.55</td>
<td>8.40</td>
<td>26.81 ± 0.02</td>
<td>16.49 ± 0.08</td>
<td>43.30 ± 0.08</td>
</tr>
<tr>
<td>519</td>
<td>60.57</td>
<td>9.55</td>
<td>26.73 ± 0.03</td>
<td>17.82 ± 0.34</td>
<td>44.55 ± 0.34</td>
</tr>
<tr>
<td>520</td>
<td>58.62</td>
<td>7.67</td>
<td>26.86 ± 0.02</td>
<td>19.03 ± 0.08</td>
<td>45.89 ± 0.09</td>
</tr>
<tr>
<td>521</td>
<td>61.75</td>
<td>7.56</td>
<td>26.87 ± 0.02</td>
<td>16.98 ± 0.23</td>
<td>43.85 ± 0.22</td>
</tr>
<tr>
<td>522</td>
<td>63.71</td>
<td>7.65</td>
<td>26.86 ± 0.02</td>
<td>15.73 ± 0.17</td>
<td>42.59 ± 0.18</td>
</tr>
<tr>
<td>523</td>
<td>62.66</td>
<td>6.53</td>
<td>26.92 ± 0.01</td>
<td>16.36 ± 0.13</td>
<td>43.29 ± 0.12</td>
</tr>
</tbody>
</table>
5.1.3.3. Gloss Test

The print gloss is obtained after the application of ink, usually in solid patches. Printed papers having high gloss can provide good color saturation, whereas printed papers with low gloss will have a dull unsaturated appearance. In most situations, papers required to carry multicolor printing need a high gloss to give intensity or color saturation. The measurement of print gloss and delta gloss of tested papers is shown in Table 14. It displays that sample 1 yields higher print gloss and can achieve higher positive delta gloss due to less ink penetration into the paper sheet. Sample 4 with latex D, on the other hand, has lower print gloss. Tested paper samples have higher print gloss in cyan and lower print gloss in yellow. A higher gloss contrast between printed and unprinted areas was found in cyan and black inks.

Table 14. Gloss measurement at 60° geometry

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper gloss</td>
<td>23.9</td>
<td>17.5</td>
<td>16.7</td>
<td>16.6</td>
<td>18.1</td>
<td>17.6</td>
<td>16.4</td>
</tr>
<tr>
<td>Print gloss</td>
<td>43.7</td>
<td>32.5</td>
<td>30.6</td>
<td>30.6</td>
<td>34.2</td>
<td>32.3</td>
<td>32.4</td>
</tr>
<tr>
<td>Delta gloss</td>
<td>19.8</td>
<td>15.0</td>
<td>13.9</td>
<td>14.0</td>
<td>16.1</td>
<td>14.7</td>
<td>16.0</td>
</tr>
<tr>
<td>Magenta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Print gloss</td>
<td>35.1</td>
<td>28.9</td>
<td>26.6</td>
<td>23.8</td>
<td>27.3</td>
<td>26.8</td>
<td>26.1</td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Print gloss</td>
<td>32.8</td>
<td>26.6</td>
<td>24.4</td>
<td>24.4</td>
<td>26.7</td>
<td>25.1</td>
<td>25.7</td>
</tr>
<tr>
<td>Delta gloss</td>
<td>8.8</td>
<td>9.1</td>
<td>7.7</td>
<td>7.7</td>
<td>8.6</td>
<td>7.5</td>
<td>9.3</td>
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<tr>
<td>Black</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Print gloss</td>
<td>41.4</td>
<td>30.3</td>
<td>29.2</td>
<td>28.1</td>
<td>31.7</td>
<td>29.8</td>
<td>29.2</td>
</tr>
<tr>
<td>Delta gloss</td>
<td>17.5</td>
<td>12.8</td>
<td>12.4</td>
<td>11.5</td>
<td>13.6</td>
<td>12.2</td>
<td>12.8</td>
</tr>
</tbody>
</table>

5.1.3.4. Print Mottle Test

A common printing defect of coated papers in multicolor printing is print mottle (irregular and unwanted variations in the printed tone). The distribution uniformity of the coating components is one factor influencing coated printing paper mottle. If the coating surface receives a uniform ink film, uneven surface binder distribution may create
differences in ink penetration, causing print mottle\textsuperscript{9, 10, 11}. Scanned solid CMYK patches were evaluated with Verity IA Color Image Analysis software. The print mottle measurement algorithm is a derivative of the Verity IA stochastic frequency distribution analysis. It quantifies the degree of mottle present in printed specimens. The greater the print mottle number, the greater the variations in surface coating structure\textsuperscript{113}. Table 15 shows the measurement of print mottle of tested paper samples. As shown in Table 15, sample 1 with latex A has lower print mottle numbers in cyan and black, while sample 4 with latex D has a lower print mottle number in magenta. All tested paper samples have smaller print mottle numbers in yellow, in other words, the print mottle in yellow is less obvious, which is understandable, because it gives least contrast.

Table 15. Print mottle measurement

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Cyan Mean</th>
<th>Std. Dev.</th>
<th>Magenta Mean</th>
<th>Std. Dev.</th>
<th>Yellow Mean</th>
<th>Std. Dev.</th>
<th>Black Mean</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.6</td>
<td>1.2</td>
<td>10.6</td>
<td>2.5</td>
<td>5.7</td>
<td>1.8</td>
<td>3.9</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>16.4</td>
<td>2.9</td>
<td>17.1</td>
<td>1.1</td>
<td>4.6</td>
<td>1.0</td>
<td>7.6</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>21.3</td>
<td>3.8</td>
<td>15.0</td>
<td>3.8</td>
<td>4.5</td>
<td>0.5</td>
<td>9.2</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>13.0</td>
<td>2.1</td>
<td>8.1</td>
<td>1.0</td>
<td>4.2</td>
<td>0.9</td>
<td>7.8</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>16.7</td>
<td>5.3</td>
<td>13.6</td>
<td>3.0</td>
<td>3.8</td>
<td>0.5</td>
<td>7.4</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>20.0</td>
<td>3.2</td>
<td>10.1</td>
<td>0.9</td>
<td>3.7</td>
<td>0.6</td>
<td>8.9</td>
<td>0.6</td>
</tr>
<tr>
<td>7</td>
<td>14.3</td>
<td>2.9</td>
<td>12.1</td>
<td>1.9</td>
<td>3.8</td>
<td>0.4</td>
<td>9.2</td>
<td>0.7</td>
</tr>
</tbody>
</table>

5.1.3.5. Color Gamut Test

The color gamut is the range of colors that a particular combination of press, ink, and print media can achieve. The wider the color gamut, the more colors the press can reproduce. Therefore, color gamut can be treated as an indicator predicting color reproduction capability of a device. The color gamut comparisons for the tested paper samples are shown in Figure 10 and Table 16. The color gamut volumes of tested
paper samples are quite similar to each other. The gamut volume of a
printer/substrate combination is the volume of the gamut figure in L\'a'b'
space. Recently, gamut volume with a given printing device has been
proposed as a measure of the quality of paper and its coating\textsuperscript{103}. The
gamut volumes are in the range of 300,000 to 325,000. In other words, the
types of latexes used in this study, resulting in quite similar substrate pore
size distribution and fluid penetration properties, didn't make many
remarkable differences in the color reproduction.

![Figure 10. Color gamut comparison for the tested paper samples](image)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Gamut Volume</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>315,000</td>
<td>3,000</td>
</tr>
<tr>
<td>2</td>
<td>321,000</td>
<td>3,000</td>
</tr>
<tr>
<td>3</td>
<td>313,000</td>
<td>4,000</td>
</tr>
<tr>
<td>4</td>
<td>312,000</td>
<td>4,000</td>
</tr>
<tr>
<td>5</td>
<td>311,000</td>
<td>4,000</td>
</tr>
<tr>
<td>6</td>
<td>312,000</td>
<td>3,000</td>
</tr>
<tr>
<td>7</td>
<td>306,000</td>
<td>4,000</td>
</tr>
</tbody>
</table>

Table 16. Gamut volumes comparison for the tested paper samples
5.1.4. Correlation Analysis for Paper Physical Properties and Printing Properties

This section investigates the correlations between paper physical properties and printing properties. Pearson's correlation coefficient was used to measure association between paper surface/physical properties and printing properties. The significant level (\( \alpha \)) was set at .05 for statistical tests. The correlation analysis results about the relationship between the paper surface/physical properties and printing properties are exhibited in Table 17.

Table 17. Pearson correlation between paper physical properties and printing properties

<table>
<thead>
<tr>
<th>Printing properties</th>
<th>Roughness</th>
<th>Formation</th>
<th>Average pore size</th>
<th>Porosity</th>
<th>Air Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print gloss</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>.000</td>
<td>-976*</td>
<td>.009</td>
<td>-.879*</td>
<td>.509</td>
</tr>
<tr>
<td>M</td>
<td>.009</td>
<td>-.880*</td>
<td>.001</td>
<td>-.956*</td>
<td>.524</td>
</tr>
<tr>
<td>Y</td>
<td>.001</td>
<td>-958*</td>
<td>.010</td>
<td>-.873*</td>
<td>.672</td>
</tr>
<tr>
<td>K</td>
<td>.001</td>
<td>-960*</td>
<td>.005</td>
<td>-.905*</td>
<td>.452</td>
</tr>
<tr>
<td>Print mottle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>.253</td>
<td>.500</td>
<td>.919</td>
<td>.048</td>
<td>.231</td>
</tr>
<tr>
<td>M</td>
<td>.755</td>
<td>.146</td>
<td>.838</td>
<td>-.096</td>
<td>.630</td>
</tr>
<tr>
<td>Y</td>
<td>.104</td>
<td>-.663</td>
<td>.074</td>
<td>-.710</td>
<td>.939</td>
</tr>
<tr>
<td>K</td>
<td>.011</td>
<td>.869*</td>
<td>.065</td>
<td>.725</td>
<td>.806</td>
</tr>
</tbody>
</table>

* Correlation (Corr.) is significant at the 0.05 level (2-tailed).

It shows that the roughness of the tested paper samples significantly correlates with print gloss at the 0.05 level. With decreasing roughness, print gloss increases. It also found that there is a strong negative relationship between formation and print gloss. There is no significant correlation between formation and print mottle. The correlations between porosity-related characteristic and printing characteristics were not clear (p value > \( \alpha = .05 \)), with the exception of air permeability. There is a strong negative relationship between air
permeability and print gloss. The less air that flows through the paper sheet, the higher the print gloss is. The air permeability of the tested paper samples also significantly correlates with print mottle in yellow and black color.

Figure 11 displays relations between roughness and printing properties. It shows that there is a strong correlation between roughness and print gloss, consistent with previous results. Print gloss increased as roughness of paper decreased. The relationship between roughness and print mottle is not clear. As shown in Figure 11, the print mottle number slightly increased as roughness of paper increased for cyan and black, that is, the more uniform the paper, the less the print mottle in cyan and black color.

![Figure 11. Relationship of Emveco roughness vs. printing properties](image)

Figure 12 to Figure 14 exhibit relations between porosity-related characteristics and printing properties. There are no strong relationships
between porosity-related characteristics and printing properties, except for air permeability. As shown in Figure 12 and Figure 13, the print gloss value slightly increased as average pore size and porosity value decreased, which means grooved structures and convergent pore geometries may decrease print gloss. Also, if more ink stays on surface of the substrate, better leveling occurs, which lead to higher gloss. According to Figure 12, Figure 13, and Table 15, print mottle slightly increased as average pore size and porosity value increased. In other words, grooved structures and convergent pore geometries may increase print mottle permanence.

Figure 12. Relationship of average pore size vs. printing properties
As shown in Figure 14, a significant relationship was found between air permeability and print gloss. The less the air flows through the paper sheet, the higher is the print gloss. This may be related to low air permeability values being observed in coatings with small pigment particle size, which also tend to generate high paper and ink gloss. The air permeability of the tested paper samples also correlates with print mottle in yellow and black colors.

5.1.5. Correlation Analysis for Surface Properties and Color Gamut

The correlation analysis results about the relationship between the paper surface properties and color gamut are exhibited in Table 18 and Figure 15. As shown in Table 18, the correlations between paper surface properties and color gamut were not clear (p value > α = .05). It was also shown in Figure 15 where those points did not cluster closely around the imaginary line of best fit.
Table 18. Pearson correlation between paper physical properties and color gamut

<table>
<thead>
<tr>
<th>Paper Properties</th>
<th>Color Gamut Volume</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>Pearson Correlation</td>
</tr>
<tr>
<td>EMVECO Roughness</td>
<td>.965</td>
<td>-.021</td>
</tr>
<tr>
<td>Formation Index</td>
<td>.436</td>
<td>-.354</td>
</tr>
<tr>
<td>Pore Size</td>
<td>.836</td>
<td>.097</td>
</tr>
<tr>
<td>Porosity</td>
<td>.415</td>
<td>.369</td>
</tr>
<tr>
<td>Air Permeability</td>
<td>.614</td>
<td>-.234</td>
</tr>
</tbody>
</table>

Figure 14. Relationship of air permeability vs. printing properties

Figure 15. Relationship of surface properties vs. color gamut
Table 19 and Figure 16 display the relationship between the paper surface properties and color gamut with newsprint (black dot) and free sheet (blue dot) substrates for reference. Table 19 indicates that strong correlations are found between color gamut and surface properties such as roughness, formation, average pore size and air permeability. The smoother the paper, the larger the gamut volume is. Gamut volume also increased as average pore size and air permeability reading decreased. As shown in Figure 16, the correlations between paper surface properties and color gamut were clear since newsprint (black dot) has relatively large roughness and porosity-related characteristics readings. The LWC paper samples (red dots), however, are clustering in the same area. That is, experimental coating formulations did not bring any drastic changes in physical properties of tasted samples, which then resulted in similar print quality color reproduction capability. It can be concluded that acrylonitrile did not modify styrene butadiene latexes to such extent that they would provide any positive changes in paper physical properties.

Table 19. Pearson correlation between paper physical properties and color gamut (with Newsprint and Free Sheet for reference)

<table>
<thead>
<tr>
<th>Paper Properties</th>
<th>Color Gamut Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
</tr>
<tr>
<td>EMVECO Roughness</td>
<td>.000</td>
</tr>
<tr>
<td>Formation Index</td>
<td>.031</td>
</tr>
<tr>
<td>Pore Size</td>
<td>.000</td>
</tr>
<tr>
<td>Porosity</td>
<td>.772</td>
</tr>
<tr>
<td>Air Permeability</td>
<td>.000</td>
</tr>
</tbody>
</table>
5.2. The Influence of Coating on the Color Gamut of Ink-jet Paper

This trial evaluated the performance of the fumed alumina and fumed silica ink-jet coatings in terms of roughness, paper gloss, optical density and color gamut.

5.2.1. Ink-jet Coating Formulations

Cationic silica (Cabot 022) and fumed alumina (Cabot 003) were used as pigments, whereas Celvol 103 fully hydrolyzed polyvinyl alcohol (PVOH) and polyvinyl pyrrolidone (PVP) served as binders. Table 20 lists the coating formulations used in this study. Table 21 shows the physical properties of coating formulations. As shown in Table 21, the final solids content of fumed alumina coatings can reach 30%, while the final solids content of cationic silica is only 18%. The viscosity of coating was measured by using a Brookfield viscometer with #4 spindle. It shows that
the addition of PVP in the fumed alumina coating significantly increases viscosity of the coating.

Table 20. Ink-jet coating formulations

<table>
<thead>
<tr>
<th>Coating</th>
<th>FA1</th>
<th>FA2</th>
<th>FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pigment</td>
<td>Fumed Alumina</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Fumed Silica</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Binder</td>
<td>PVOH</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>PVP</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Surfactant</td>
<td>Foamaster</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 21. Properties of ink-jet coating formulations

<table>
<thead>
<tr>
<th>Coating</th>
<th>Final Solids content, %</th>
<th>pH</th>
<th>Viscosity, cP (at 100 rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA1</td>
<td>30.74</td>
<td>4.22</td>
<td>316 (#4 spindle)</td>
</tr>
<tr>
<td>FA2</td>
<td>30.55</td>
<td>4.00</td>
<td>810 (#4 spindle)</td>
</tr>
<tr>
<td>FS</td>
<td>18.67</td>
<td>9.64</td>
<td>232 (#4 spindle)</td>
</tr>
</tbody>
</table>

The base sheet used in coating experiments was sized paper. Physical properties of the base sheet were basis weight of 81.85 g/m², Parker Print Surf roughness of 6.42 μm, TAPPI brightness of 92.04%, and paper gloss (at 75°) of 16.1. Coatings were prepared using various Mayer rods (5-52) and air dried. Three different coat weights were applied: 7 ± 1 g/m², 12 ± 1 g/m², and 22 ± 1 g/m². The coated ink-jet papers were calendered on the soft-hot nip calender (60-65°C) through 3 nips before performing any gloss and roughness measurements.

5.2.2. Coated Ink-jet Paper Properties

Figure 17 and Figure 18 display roughness and paper gloss properties for each coating, respectively. It is suggested by the data in Figure 17, that fumed alumina coatings (FA1 and FA2) tend to orient and pack together tightly, producing a smoother surface than cationic silica coatings (FS). The roughness of the coating increased with increasing coat
weight in FA2 and FS, and decreased with increasing coat weight in FA1. Due to low solids content of cationic silica coating (18%), excess coating water penetrated into the base paper, resulting in fiber swelling. The roughness of fumed alumina coatings was in the range of 2.4 to 3.7 μm, while the cationic silica coating had a wider range of roughness, 2.5 to 5.5 μm.

Gloss is a function of surface smoothness. The highest gloss was found in FA1 coating (Figure 18), which is in accordance with its smoothest surface (Figure 17). The gloss of fumed alumina pigments was higher than that of fumed cationic silica pigments. The paper gloss values of FA1 coating are up to 40%, the gloss of FA2 coating is in the range of 35% to 40%, and the FS coating has lower gloss values of 23% to 30%. The lower gloss and increase in roughness at higher coat weights is likely due to coating “cracks” known for fumed silica coatings\textsuperscript{117}. 

Figure 17. Ink-jet paper roughness as a function of coat weight
5.2.3. Optical Density

Figure 19 shows optical densities for each coating. Optical densities are averaged for the process colors, cyan, magenta, yellow, and black and plotted for the three coatings and two ink-jet printers. On average, the tested coatings provided maximum densities when printed with the dye-based inks independent of the coat weight. The positive charge of cationic silica contributes to the dye fixation of negatively charged dye-based inks.
5.2.4. Color Gamut

Color gamut comparisons for all coating formulations are illustrated in Figure 20 and Figure 21. As shown in Figure 21, the dye-based printer has better color capability for all formulated coatings, which agrees with the theory about smaller colorant particles give more color strength\(^3\). Dye based inks also gave higher optical densities than pigmented ones, as presented earlier.

Figure 20 and Figure 21 show that cationic silica coating (FS) had good performance with the dye-based printer, although it had slightly worse performance with the pigment-based printer. For fumed alumina coatings, the addition of PVP did not expand the color gamut. Fumed alumina coating (FA1) with PVOH alone has better color capability, which is very apparent in the case of the dye-based inks.

![Figure 20. Gamut volume as a function of coating formulation (pigment-based printer)](image)
Figure 21. Gamut volume as a function of coating formulation (dye-based printer)

5.2.5. Effect of Coat Weight on Optical Density and Color Gamut

The influence of coating formulation and coat weight on optical density and color gamut are shown in Figure 22 and Figure 23, respectively. Also seen in Figure 22, the density values of fumed alumina coatings increase slightly as coat weight increased when the pigment-based printer was employed. Coated samples printed with dye-based printer did not follow this trend. As shown in Figure 22, both the coat weight and coating color influenced the optical density.

Generally, density increases as the coat weight is increased, since increasing the amount of coating materials improves the uniformity of the coated surface. In this study, however, not all coatings followed this trend. When the pigment-based printer was used, the optical density values of fumed alumina coatings increase as coat weight increased. The black density value of cationic silica coating (FS), however, decreased as coat weight increased, possibly due to the aforementioned cracks. When the dye-based printer was used, the density values of coatings decrease as coat weight increased, with the exception of the cyan color, meaning that
the dye could penetrate more inside the thicker coating structure. However, dyed cyan ink had the opposite behavior.

In Figure 22, the color gamut expands with increasing coat weights except for the FA2 coating. The addition of PVP did not expand the color gamut. Cationic silica coating (FS) has better color capability with the dye-based printer. When printed on the pigment-based printer, however, the FS coating yields a smaller color gamut.

Figure 23. Effect of coating formulation and coat weight on gamut volume
5.2.6 Effect of Calendering on Optical Density and Color Gamut

Calendering is usually the final step in the production of a coated paper. It has a decisive influence on many end-use properties. Usually, coated papers are calendered to increase gloss and improve smoothness. Figure 24 shows the effect of calendering on surface roughness and paper gloss. As expected, calendered paper has a smoother and glossier surface. The steepest slopes, decreasing roughness and increasing gloss values, are found with the fumed alumina coatings. In order to further investigate the influence of calendering on optical density and color gamut, the coated ink-jet papers with coat weight 12 g/m² were calendered on the soft-hot nip calender (60-65°C) through 6 nips, providing data to compare with 3 nips conditions.

![Graph showing effect of calendering on roughness and gloss](image)

Figure 24. Effect of calendering on roughness and gloss

The effect of calendering on density values was exhibited in Figure 25. Density consequently increased, presumably due to a more closed pore structure of the treated coating surface. However, density values of the tested coatings did not all obtain the benefits from the higher degree of calendering. Calendering can cause coating layer compression, which in turn affects the ink setting properties. As seen in Figure 25, calendering has less influence on coating samples when printed on the pigment-based
printer, most likely due to better holdout ability of pigmented ink on the more open surface. Magenta density values, however, decrease with a higher degree of calendering. Calendering has more impact on coating samples when printed on the dye-based printer, maybe due to restricted penetration of dye into the coating layer. A higher degree of calendering can improve optical density. The degree of calendering has less influence on the FA2 coating, which contained the PVP binder.

![Graphs and diagrams showing the effect of calendering on optical density values and gamut volume.](image)

Figure 25. Effect of calendering on optical density values (coat weight: 12 gsm)

Figure 26 shows the effect of calendering on gamut volume. The degree of calendering has a small positive effect on the gamut volume of the samples. The gamut volume of cationic silica coating (FS), however, decreases with a higher degree of calendering for the pigment printer.
5. 3. The Effect of Paper Properties on the Color Reproduction for Digital Proofing

The proof-press color matching highly depends on the range of colors and tonal ranges that press and digital printers can reproduce. Therefore, the color gamut of print combinations of press/inks/papers versus digital proofing system must be well defined. This trial discussed the color reproduction of digital proofing from the point of view of paper properties. The correlations between paper properties and color gamut (gamut volume) were also investigated.

5. 3. 1. Color Gamut Analysis of Digital Proofing

In order to analyze the color gamut for a device, an ICC profile needs to be created. The ECI2002R CMYK test target designed for DTP 70 spectrophotometer was employed for this trial. An Epson Stylus Pro 4000 printer with UltraChrome pigmented inks was selected as digital proofing device. The Epson Stylus Pro 4000 printer applies drop-on-demand technology to form droplets, which land on the paper surface. The digital signal changes by heating or using a piezoelectric effect\textsuperscript{32,33}. 

![Figure 26. Effect of calendering on gamut volume (coat weight: 12 g/m\textsuperscript{2})](image_url)
For proofing device, the ECI2002R CMYK chart was printed on the tested proofing substrates via CGS ORIS RIP software. Those printed charts were measured with an X-Rite DTP70 spectrophotometer, operated by GretagMacbeth Measure Tool 5.0.7 software. The measurement files were used to generate profiles using GretagMacbeth ProfileMaker Pro 5.0.7. ICC profiles were then loaded into CHROMiX ColorThink Pro 3 software and the gamut volumes of the ICC profiles were determined. The proof-press color gamut comparison for the free sheet (FS), light weight coated (LWC) and newsprint is discussed below.

5.3.1.1. Free Sheet (FS)

The free sheet was printed on the Epson Stylus 4000 digital printer and Cerutti rotogravure press. When proofing on the free sheet coated paper with the Epson Stylus Pro 4000 printer, it was found that UltraChrome inks have severe ink smearing problems and cannot lay on the paper surface properly. Therefore, free sheet coated paper with Epson Stylus Pro 4000 printer combination was excluded in further discussion. Figure 27 illustrates the proof-press color gamut comparison for the free sheet coated paper. As seen from Figure 27, proofing papers, printed via Epson Stylus Pro 4000 printer, yield wider color gamuts than press gamut for the free sheet coated paper.

Figure 27. Proof-press color gamut comparison for the free sheet coated paper
5.3.1.2. Light Weight Coated Paper (LWC)

Figure 28 illustrates the proof-press color gamut comparison for the light weight coated paper. When proofing on the light weight coated paper, the Epson Stylus Pro 4000 printer yielded a greater color gamut in the yellow area, but a smaller color gamut in magenta and red regions. The press gamut is larger in the lower L' values area, where the Epson Stylus Pro 4000 cannot achieve the dark shadow details. As expected, the color gamuts of selected proofing papers were wider than that of light weight coated paper that was printed via the Cerutti rotogravure web press.

Figure 28. Proof-press color gamut comparison for the light weight coated paper

5.3.1.3. Newsprint

The proof-press color gamut comparison for the newsprint printed via the Epson Stylus Pro 4000 printer is shown in Figure 29. The color gamuts of proofing papers were all wider than that of newsprint that was printed via the Cerutti rotogravure web press. When proofing on the newsprint, the color gamut of the Epson Stylus Pro 4000 printer is similar to that of press. The Epson Stylus Pro 4000 printer gamut is larger in the higher L' values area, while the press gamut is larger in the lower L' values area.
5.3.1.4. Gamut Volume Comparison

Table 22 shows the proof-press color gamut comparisons in terms of gamut volume. Compared to the press gamut volume, the Epson Stylus Pro 4000 printer has larger gamut volume for the selected proofing papers, but a smaller gamut volume for the actual production printing substrates.

Table 22. Gamut volume comparisons for recommended and printing substrates

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Cerutti Rotogravure Web Press</th>
<th>Epson Stylus Pro 4000 Printer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>Free Sheet</td>
<td>332,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Light Weight Coated</td>
<td>315,000</td>
<td>3,000</td>
</tr>
<tr>
<td>Newsprint</td>
<td>149,000</td>
<td>2,200</td>
</tr>
<tr>
<td>Semimatte Photo Paper</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Pearl Proof Paper</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Selected Proof Paper</td>
<td>------</td>
<td>------</td>
</tr>
</tbody>
</table>

5.3.2. Paper Properties of Press Paper and Proofing Paper

5.3.2.1. Surface Properties

Roughness and formation measurements of tested substrates are shown in Table 23. Generally, coated papers tend to have a smoother and more uniform surface. The average roughness readings for the proofing papers are in the range of 0.7 to 1.2 micron. Compared to other papers, newsprint tends to have a rougher surface and a larger standard deviation.
value. It is interesting to note that light weight coated paper has poor formation. The uniformity of newsprint used in this study is better than that of light weight coated paper.

Table 23. Roughness measurement

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Emveco roughness [$\mu$m]</th>
<th>Formation Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>Free Sheet</td>
<td>0.96</td>
<td>0.12</td>
</tr>
<tr>
<td>Light Weight Coated</td>
<td>1.38</td>
<td>0.14</td>
</tr>
<tr>
<td>Newsprint</td>
<td>3.03</td>
<td>0.13</td>
</tr>
<tr>
<td>Semimatte Photo Paper</td>
<td>1.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Pearl Proof Paper</td>
<td>0.78</td>
<td>0.06</td>
</tr>
<tr>
<td>Selected Proof Paper</td>
<td>1.13</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 24 shows that the highest percent porosity was found in newsprint with 61.4%, followed by light weight coated (59.8%), free sheet (41.3%), pearl proof paper (37.3%), and semimatte photo paper (36.7%). Selected proof paper has the lowest percent porosity at 26.4%. Newsprint has the highest air permeability value of $9.27 \times 10^{-4}$ $\mu$m$^2$ and largest standard deviation value, compared to the other substrates. The average pore size readings for the proofing papers are in the range of 25 to 50 nm, whereas the average pore size readings for gravure publication printing papers are larger than 200 nm. The average pore size of newsprint is up to 546 nm.

Table 24. Porosity-related characteristics

<table>
<thead>
<tr>
<th>Substrates</th>
<th>Total pore area [m$^2$/g]</th>
<th>Ave. pore diameter [nm]</th>
<th>Porosity [%]</th>
<th>Air permeability [$\mu$m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Sheet</td>
<td>16.0</td>
<td>204</td>
<td>41.3</td>
<td>$11.1 \times 10^6$</td>
</tr>
<tr>
<td>Light Weight Coated</td>
<td>16.3</td>
<td>203</td>
<td>59.8</td>
<td>$10.6 \times 10^6$</td>
</tr>
<tr>
<td>Newsprint</td>
<td>6.49</td>
<td>546</td>
<td>61.4</td>
<td>$927 \times 10^4$</td>
</tr>
<tr>
<td>Semimatte Photo Paper</td>
<td>36.9</td>
<td>47.4</td>
<td>36.7</td>
<td>$8.9 \times 10^4$</td>
</tr>
<tr>
<td>Pearl Proof Paper</td>
<td>43.9</td>
<td>36.1</td>
<td>37.3</td>
<td>$0.36 \times 10^6$</td>
</tr>
<tr>
<td>Selected Proof Paper</td>
<td>41.2</td>
<td>28.6</td>
<td>26.4</td>
<td>$1.24 \times 10^6$</td>
</tr>
</tbody>
</table>
The pore size distribution curves are presented in Figure 30. The proofing papers show two peak groups of pore sizes between 1500 to 1650 nm and 12 to 20 nm, respectively. Light weight coated paper and free sheet have one peak group of pore size between 800 to 1000 nm, whereas newsprint shows one maximum centered at 7000 nm. A coating is designed to make surfaces smoother and less porous; therefore these results are not very surprising. A large maximum for newsprint is quite understandable, because newsprint is not coated. The pore sizes over 10,000 nm were not considered, since they originate from raw stock porosity and possible artifacts.

Figure 30. Pore size distribution from mercury porosimetry curves

5.3.2.2. Optical Properties

The optical properties measurements of tested papers are summarized in Table 25. Whiteness provides a better idea about papers' color reproduction capability, because it measures reflectance across all
wavelengths in the visible light spectrum. Semimatte photo paper and selected proof paper containing optical brighteners were measured automatically by a built-in ultra violet cut-off filter. It is not surprising that proofing papers have higher percent brightness and whiteness. The opacity readings for all tested papers are in the range of 90% to 97%, with the exception of light weight coated paper (with relatively low opacity of 82%). The highest paper gloss % was found in Pearl Proof paper with 63%. The free sheet coated paper has high paper gloss value of 62%, but has the largest standard deviation value (2.5). Newsprint has the lowest paper gloss %, compared to other substrates.

Table 25. Optical properties measurement

<table>
<thead>
<tr>
<th>Substrates</th>
<th>TAPPI Brightness [%]</th>
<th>ASTM Whiteness</th>
<th>TAPPI Opacity [%]</th>
<th>Paper Gloss at 75° [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>Free Sheet</td>
<td>79.3</td>
<td>0.2</td>
<td>77.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Light Weight Coated</td>
<td>69.9</td>
<td>0.1</td>
<td>42.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Newsprint</td>
<td>56.4</td>
<td>0.5</td>
<td>34.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Semimatte Photo Paper</td>
<td>95.7</td>
<td>0.2</td>
<td>109.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Pearl Proof Paper</td>
<td>89.3</td>
<td>0.1</td>
<td>89.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Selected Proof Paper</td>
<td>93.0</td>
<td>0.3</td>
<td>99.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Figure 31 represents color spectra for all tested papers. The color spectra data were measured by using GretagMacbeth SpectroScanT spectrophotometer. As shown in Figure 31, proofing papers, especially Pearl Proof, tend to have higher reflectance values in the blue region (420-470 nm), resulting in blue white appearance. Conversely, light weight coated paper and newsprint has higher light reflectance in the red region of the spectrum and thus looks warm white.
5.3.3. The Effect of Paper Properties on Color Reproduction

Pearson's correlation coefficient was used to measure the association between gamut volume and paper properties. The correlation analysis between gamut volume and paper properties for the Epson Stylus Pro 4000 printer is displayed in Table 26. According to Table 26, the gamut volume of the tested papers significantly correlates with all paper properties at the 0.05 level. It shows that there is a strong positive relationship between gamut volume and formation index, whereas the relationship between gamut volume and roughness is negative, meaning smoother papers have larger color gamuts. Gamut volume also has a negative relationship with porosity-related characteristics. It also found that the relationships between gamut volume and optical properties are positive. The brighter and whiter the paper is, the larger the gamut volume. This is consistent with most observations, but there are some exceptions.
Table 26. Pearson correlation between gamut volume and paper properties

<table>
<thead>
<tr>
<th>Paper Properties</th>
<th>Color Gamut Volume</th>
<th>Pearson Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample Size</td>
<td>Sig. (2-tailed)</td>
</tr>
<tr>
<td>EMVECO Roughness</td>
<td>5</td>
<td>.000</td>
</tr>
<tr>
<td>Formation Index</td>
<td>5</td>
<td>.000</td>
</tr>
<tr>
<td>Porosity</td>
<td>5</td>
<td>.000</td>
</tr>
<tr>
<td>Pore Size</td>
<td>5</td>
<td>.041</td>
</tr>
<tr>
<td>Air Permeability</td>
<td>5</td>
<td>.000</td>
</tr>
<tr>
<td>Brightness</td>
<td>5</td>
<td>.000</td>
</tr>
<tr>
<td>Whiteness</td>
<td>5</td>
<td>.000</td>
</tr>
<tr>
<td>Opacity</td>
<td>5</td>
<td>.000</td>
</tr>
<tr>
<td>Paper Gloss</td>
<td>5</td>
<td>.000</td>
</tr>
</tbody>
</table>

* Correlation is significant at the 0.05 level (2-tailed).

5.4. Proof-press Color Matching Capability

The quality of proof-press color matching was evaluated in terms of color difference ($\Delta E^{*2000}$) and process consistency. The former is a valuable tool to determine color accuracy in the proofing systems and does a better job to determine a $\Delta E$ that more accurately reflects how the eye sees color, compared to the $\Delta E^{*ab}$ method\textsuperscript{35,118}. The latter uses statistical techniques to measure and analyze the variation in processes and provides a process capability ratio to identify how capable a process is of meeting specifications. The $\Delta E^{*2000}$, between a sample color $L_2a_2b_2$ and a reference color $L_1a_1b_1$, was calculated based on the following equation\textsuperscript{119}:

$$
\Delta E^{*2000} = \sqrt{\left(\frac{\Delta L'}{K_{LS_L}}\right)^2 + \left(\frac{\Delta C'}{K_{CS_C}}\right)^2 + \left(\frac{\Delta H'}{K_{HS_H}}\right)^2 + R_T \left(\frac{\Delta C'}{K_{CS_C}}\right)\left(\frac{\Delta H'}{K_{HS_H}}\right)}
$$

(18)

where

$$
\bar{L} = (L_1 + L_2)/2 \\
C_1 = \sqrt{a_1^2 + b_1^2} \\
C_2 = \sqrt{a_2^2 + b_2^2} \\
\bar{C} = (C_1 + C_2)/2 \\
G = \left(1 - \sqrt{\frac{\bar{C}}{\bar{C} + 25}}\right)/2
$$

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\[ a'_1 = a_1(1 + G) \]
\[ a'_2 = a_2(1 + G) \]
\[ c'_1 = \sqrt{a'_1^2 + b_1^2} \]
\[ c'_2 = \sqrt{a'_2^2 + b_2^2} \]
\[ \bar{c}' = (c'_1 + c'_2)/2 \]
\[ h'_1 = \begin{cases} 
\tan^{-1}(b_1/a_1) & \text{if } \tan^{-1}(b_1/a_1) > 0 \\
\tan^{-1}(b_1/a_1) + 360° & \text{if } \tan^{-1}(b_1/a_1) < 0 
\end{cases} \]
\[ h'_2 = \begin{cases} 
\tan^{-1}(b_2/a_2) & \text{if } \tan^{-1}(b_2/a_2) > 0 \\
\tan^{-1}(b_2/a_2) + 360° & \text{if } \tan^{-1}(b_2/a_2) < 0 
\end{cases} \]
\[ \bar{h}' = \begin{cases} 
(h'_1 + h'_2 + 360°)/2 & |h'_1 - h'_2| > 180° \\
(h'_1 + h'_2)/2 & |h'_1 - h'_2| \leq 180° 
\end{cases} \]
\[ T = 1 - 0.17 \cos (\bar{h}' - 30°) + 0.24 \cos (2\bar{h}') + 0.32 \cos (3\bar{h}' + 6°) - 20 \cos (4\bar{h}' - 63°) \]
\[ \Delta h' = \begin{cases} 
h'_2 - h'_1 & |h'_2 - h'_1| \leq 180° \\
h'_2 - h'_1 + 360° & |h'_2 - h'_1| > 180°; h'_2 \leq h'_1 \\
h'_2 - h'_1 - 360° & |h'_2 - h'_1| > 180°; h'_2 > h'_1 
\end{cases} \]
\[ \Delta L' = L_2 - L_1 \]
\[ \Delta C' = \bar{C}' - C'_1 \]
\[ \Delta H' = 2\sqrt{C'_1C'_2} \sin (\Delta h'/2) \]
\[ S_L = 1 + \frac{0.015(L' - 50)^2}{\sqrt{20 + (L' - 50)^2}} \]
\[ S_c = 1 + 0.045\bar{c}' \]
\[ S_H = 1 + 0.015\bar{c}' T \]
\[ \Delta \theta = 30 \exp \left\{ - \left( \frac{\bar{H}' - 275°}{25} \right)^2 \right\} \]
\[ R_c = \frac{\bar{c}^{-7}}{\sqrt{\bar{c}'^7 + 25^7}} \]
\[ R_T = -2R_c \sin(2\Delta \theta) \]
\[ K_L = 1 \text{ default} \]
\[ K_c = 1 \text{ default} \]
\[ K_H = 1 \text{ default} \]
5.4.1. Proof-press Color Matching Procedures

Three gravure publication printing substrates—free sheet coated paper (FS), light weight coated paper (LWC), and newsprint (News)—were used as the color matching targets. These papers were collected from the gravure publication printing trial. Thirty samples of each substrates were collected and measured with an X-Rite DTP70 spectrophotometer, and the average L*a*b* value was computed as target values. Three types of manufacturer recommended proofing papers—Semimatte Photo Paper (PSPP), Pearl Proof Paper (Pearl), and Selected Proof Paper (Selected) were tested and compared.

Two commercially available inkjet digital printers, an Epson Stylus Pro 4000 printer with UltraChrome pigmented inks and an Epson Stylus Pro 9800 printer with UltraChrome K3 inks, were combined with the commercially available GMG ColorProof RIP and tested for selected proofing substrates. ICC profiles were generated for the digital printers by using MonacoPROFILER 4.8. The device was profiled as a CMYK device. The ECI2002R CMYK test target designed for a DTP 70 spectrophotometer was employed for this study.

The target L*a*b* values generated from the gravure publication printing substrates were loaded into the RIP’s color matching function. The GMG ColorProof RIP then performs proof-press color matching by controlling CMYK ink amounts to match L*a*b* values between digital printer (proof) and target (press). Once the good color matching result was achieved (the smallest average ΔE value of color patches of ECI2002R chart was obtained), 15 ECI2002R charts were printed out for each tested print combination. Those charts were measured with the DTP 70
spectrophotometer and the color difference ($\Delta E_{2000}$) values between proof and press were recorded and collected to examine the color matching capability and process consistency.

5.4.2. Proof-press Color Matching Capability for Free Sheet

The proof-press color matching results for the Free Sheet are listed in Table 27. As shown in Table 27, the smallest average $\Delta E_{2000}$ value was found in the Epson Stylus Pro 4000 printer/Selected Proof Paper combination with $\Delta E_{2000}$ value of 0.79. Compared to other print combinations, the Epson Stylus Pro 9800 printer/Semimatte Photo combination tends to have a larger $\Delta E_{2000}$ value and a larger standard deviation. The calculated differences in paper white for target (press) and proof $L\,a\,b'$ values are in the range of 4.0-4.6. In other words, six print combinations didn't have very good paper white simulation ability to match paper white. The maximum $\Delta E_{2000}$ values of six print combinations are in the range of 5.1-13.1, while the minimum $\Delta E_{2000}$ values are in the range of 0.01-0.05.

Table 27. Proof-press color matching results for Free Sheet (FS)

<table>
<thead>
<tr>
<th>Print Combination</th>
<th>Ave. $\Delta E$</th>
<th>Std. Dev.</th>
<th>Paper white</th>
<th>Std. Dev.</th>
<th>Max. $\Delta E$</th>
<th>Min. $\Delta E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP4000/Pearl</td>
<td>0.84</td>
<td>0.01</td>
<td>4.18</td>
<td>0.14</td>
<td>5.55</td>
<td>0.05</td>
</tr>
<tr>
<td>EP4000/PSP</td>
<td>0.99</td>
<td>0.04</td>
<td>4.10</td>
<td>0.08</td>
<td>13.02</td>
<td>0.04</td>
</tr>
<tr>
<td>EP4000/Selected</td>
<td>0.79</td>
<td>0.02</td>
<td>4.03</td>
<td>0.09</td>
<td>6.03</td>
<td>0.04</td>
</tr>
<tr>
<td>EP9800/Pearl</td>
<td>0.80</td>
<td>0.02</td>
<td>4.53</td>
<td>0.11</td>
<td>5.75</td>
<td>0.01</td>
</tr>
<tr>
<td>EP9800/PSP</td>
<td>1.01</td>
<td>0.05</td>
<td>4.39</td>
<td>0.13</td>
<td>7.92</td>
<td>0.02</td>
</tr>
<tr>
<td>EP9800/Selected</td>
<td>0.84</td>
<td>0.01</td>
<td>4.16</td>
<td>0.27</td>
<td>5.10</td>
<td>0.04</td>
</tr>
</tbody>
</table>
5.4.2. Proof-press Color Matching Capability for LWC Paper

Table 28 displays the proof-press color matching results for the Light Weight Coated paper. Print combinations of Epson Stylus Pro 4000 printer/Selected Proof Paper and Epson Stylus Pro 9800 printer/Pearl Proof Paper have smaller average $\Delta E^{*2000}$ values. Compared to other print combinations, the Epson Stylus Pro 4000 printer/Semimatte Photo combination tends to have a larger $\Delta E^{*2000}$ value and a larger standard deviation value. Among six print combinations, the Epson Stylus Pro 4000 printer/Selected Proof Paper has better paper white simulation ability in terms of lower paper white color difference between proof and press. The maximum $\Delta E^{*2000}$ values of six print combinations are in the range of 3.6-14.0, while the minimum $\Delta E^{*2000}$ values are in the range of 0.02-0.07.

<table>
<thead>
<tr>
<th>Print Combination</th>
<th>Ave. $\Delta E$</th>
<th>Std. Dev.</th>
<th>Paper white</th>
<th>Std. Dev.</th>
<th>Max. $\Delta E$</th>
<th>Min. $\Delta E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP4000/Pearl</td>
<td>0.79</td>
<td>0.05</td>
<td>2.59</td>
<td>0.11</td>
<td>3.66</td>
<td>0.07</td>
</tr>
<tr>
<td>EP4000/PSPP</td>
<td>0.94</td>
<td>0.01</td>
<td>1.97</td>
<td>0.04</td>
<td>13.91</td>
<td>0.04</td>
</tr>
<tr>
<td>EP4000/Selected</td>
<td>0.71</td>
<td>0.03</td>
<td>1.71</td>
<td>0.16</td>
<td>8.22</td>
<td>0.03</td>
</tr>
<tr>
<td>EP9800/Pearl</td>
<td>0.71</td>
<td>0.01</td>
<td>3.58</td>
<td>0.09</td>
<td>6.09</td>
<td>0.04</td>
</tr>
<tr>
<td>EP9800/PSPP</td>
<td>0.85</td>
<td>0.05</td>
<td>2.51</td>
<td>0.15</td>
<td>10.94</td>
<td>0.02</td>
</tr>
<tr>
<td>EP9800/Selected</td>
<td>0.77</td>
<td>0.02</td>
<td>2.26</td>
<td>0.11</td>
<td>4.97</td>
<td>0.04</td>
</tr>
</tbody>
</table>

5.4.3. Proof-press Color Matching Capability for Newsprint

The proof-press color matching results for the Newsprint is exhibited in Table 29. Print combinations of the Epson Stylus Pro 4000 printer/Semimatte Photo Paper and the Epson Stylus Pro 9800 printer/Semimatte Photo Paper have smaller average $\Delta E^{*2000}$ values, while the print combinations of Epson Stylus Pro 4000 printer/Pearl Proof Paper and Epson Stylus Pro 9800 printer/Selected Proof Paper have larger average $\Delta E^{*2000}$ values. Among six print combinations, the Epson Stylus Pro 4000
printer/Semimatte Photo Paper has better paper white simulation ability in terms of lower paper white color difference between proof and press. The maximum \( \Delta E^*_{2000} \) values of six print combinations are in the range of 3.0-11.0, while the minimum \( \Delta E^*_{2000} \) values are in the range of 0.02-0.04.

Table 29. Proof-press color matching results for newsprint

<table>
<thead>
<tr>
<th>Print Combination</th>
<th>Ave. ( \Delta E )</th>
<th>Std. Dev.</th>
<th>Paper white</th>
<th>Std. Dev.</th>
<th>Max. ( \Delta E )</th>
<th>Min. ( \Delta E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP4000/Pearl</td>
<td>0.74</td>
<td>0.07</td>
<td>2.91</td>
<td>0.21</td>
<td>3.21</td>
<td>0.03</td>
</tr>
<tr>
<td>EP4000/PSSP</td>
<td>0.64</td>
<td>0.01</td>
<td>2.52</td>
<td>0.09</td>
<td>8.33</td>
<td>0.03</td>
</tr>
<tr>
<td>EP4000/Selected</td>
<td>0.66</td>
<td>0.06</td>
<td>2.17</td>
<td>0.08</td>
<td>2.97</td>
<td>0.02</td>
</tr>
<tr>
<td>EP9800/Pearl</td>
<td>0.65</td>
<td>0.03</td>
<td>5.50</td>
<td>0.10</td>
<td>10.88</td>
<td>0.03</td>
</tr>
<tr>
<td>EP9800/PSSP</td>
<td>0.64</td>
<td>0.03</td>
<td>2.90</td>
<td>0.13</td>
<td>5.23</td>
<td>0.04</td>
</tr>
<tr>
<td>EP9800/Selected</td>
<td>0.74</td>
<td>0.03</td>
<td>3.09</td>
<td>0.12</td>
<td>6.28</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Figure 32 summaries the proof-press color matching results (average \( \Delta E^*_{2000} \)) for gravure publication printing substrates. As shown in Figure 32, print combinations of Epson Stylus Pro 4000 printer/Selected Proof Paper (blue-triangle dot) and Epson Stylus Pro 9800 printer/Pearl Proof Paper (cyan-square dot) have smaller average \( \Delta E^*_{2000} \) values for Free Sheet, Light Weight Coated, and Newsprint. The Epson Stylus Pro 4000 printer/Semimatte Photo Paper (green-circle dot) yielded smallest \( \Delta E^*_{2000} \) value for Newsprint. Among three gravure publication substrates, Free Sheet is the hardest substrate to match, while Newsprint is the easiest one to match. Overall, with the aid of color management software, the average \( \Delta E^*_{2000} \) values are all controlled and have value less than 1.0.
5.4.4. Paper White Simulation

It is well known that color appearance will be affected by the surrounding colors, especially when it comes to proof-press color matching. The paper color of Light Weight Coated and newsprint is yellowish, while paper color of the Free Sheet is bluish. Proofing papers, on the other hand, tend to have a bluish paper white. The smaller the ΔE in paper white, the less influence by the paper color and better match to the reference press sheet by visual assessment. Figure 33 shows that print combinations of Epson Stylus Pro 4000 printer/Selected Proof Paper (blue-triangle dot) has the smallest paper white ΔE values, while Epson Stylus Pro 9800 printer/Pearl Proof Paper (cyan-square dot) print combination has the largest paper white ΔE values for all gravure publication printing substrates. That is, the Epson Stylus Pro 4000 printer/Selected Proof Paper combination has better paper white simulation ability. Among three gravure publication substrates, the Free Sheet is the hardest substrate to match, while Light Weight Coated paper is the easier one to match. The paper white ΔE values vary from 1.6 to 5.6.
Table 30 lists the comparisons of paper white $L^*a^*b^*$ values for press and proofing papers. In order to simulate paper white of production paper, software will put some "scum" dots on the paper white area of proofing paper. As shown in Table 30, proofing paper matches paper white by decreasing lightness and changing chroma values, resulting in different degrees of paper white color difference. Thereby, when comparing press sheet and proofing paper side by side, the differences can be noticed. Effort must be taken to improve paper white simulation.

Table 30. $L^*a^*b^*$ values comparisons for paper white (press vs. proofing)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L^*$</td>
<td>$a^*$</td>
</tr>
<tr>
<td>Free Sheet</td>
<td>92.14</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LWC</td>
<td>88.10</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Newsprint</td>
<td>84.53</td>
<td>1.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.4.5. Process Capability Analyses

For the proof-press color matching, the repeatability and consistency of proofing systems need to be considered. The color matching process consistency and capability of the digital printers are discussed. Individual Control Chart (I Chart) and Capability Analyses were used to analyze the consistency. Process capability ratio (PCR or Cp index) is the simplest tool to measure process capability, which is expressed as the ratio of the specification range to the process range. The Cp ratio can be expressed as "(upper specification limit - lower specification limit)/(6*Sigma).". The higher the Cp index, the more capable or more consistent the process is\(^ \text{120} \).

In this trial, the relative PCR were compared between different print combinations due to the lack of historical parameters of lower specification limit (LSL) and upper specification limit (USL) for the color differences. After eliminating all out-of-control points, the final LSL and USL (as shown in Table 31) are obtained by subtracting from and adding to the average 3*Sigma for each print combination (the average Sigma was computed from the Sigmas of six print combinations).

Table 31. The LSL\(_{\text{final}}\) and USL\(_{\text{final}}\) of each print combination

<table>
<thead>
<tr>
<th>Print Combination</th>
<th>Free Sheet</th>
<th>LWC</th>
<th>Newsprint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LSL</td>
<td>USL</td>
<td>LSL</td>
</tr>
<tr>
<td>EP4000/Pearl</td>
<td>0.82</td>
<td>0.87</td>
<td>0.78</td>
</tr>
<tr>
<td>EP4000/PSPP</td>
<td>0.94</td>
<td>1.00</td>
<td>0.92</td>
</tr>
<tr>
<td>EP4000/Selected</td>
<td>0.76</td>
<td>0.81</td>
<td>0.68</td>
</tr>
<tr>
<td>EP9800/Pearl</td>
<td>0.77</td>
<td>0.82</td>
<td>0.69</td>
</tr>
<tr>
<td>EP9800/PSPP</td>
<td>0.99</td>
<td>1.04</td>
<td>0.80</td>
</tr>
<tr>
<td>EP9800/Selected</td>
<td>0.81</td>
<td>0.86</td>
<td>0.74</td>
</tr>
</tbody>
</table>

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The capability analyses of color matching for the print combinations are exhibited in Table 32 and Figure 34. For the Free Sheet, as shown in Table 32 and Figure 34, the pearl proof paper printed via the Epson Stylus Pro 9800 has the largest relative PCR (Cp = 3.46), that is, the pearl proof paper printed via the Epson Stylus Pro 9800 printer was the most capable print combination of producing consistent ΔE value among the six in terms of relative PCR. The relative PCR for all print combinations are over 1.00, with the exception of the Epson Stylus Pro 9800 printer/Semimatte Photo Paper (PSPP) combination. For the Light Weight Coated paper (LWC), the Selected Proof Paper printed via the Epson Stylus Pro 4000 printer has the largest relative PCR (Cp = 2.52), followed by the Epson Stylus Pro 9800 printer/Selected Proof Paper (Cp = 1.89), and Epson Stylus Pro 4000 printer/Pearl Proof Paper (Cp = 1.13). For the Newsprint, the largest relative PCR was found for the Epson Stylus Pro 9800 printer/Semimatte Photo Paper (Cp = 2.13). The relative PCR for all print combinations are over 1.00, with exception of the Epson Stylus Pro 4000 printer/Selected Proof Paper combination.

<table>
<thead>
<tr>
<th>Print Combination</th>
<th>Free Sheet</th>
<th>LWC</th>
<th>Newsprint</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP4000/Pearl</td>
<td>1.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EP4000/PSPP</td>
<td>1.18</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>EP4000/Selected</td>
<td>1.35</td>
<td>2.52</td>
<td>0.44</td>
</tr>
<tr>
<td>EP9800/Pearl</td>
<td>3.46</td>
<td>0.76</td>
<td>1.36</td>
</tr>
<tr>
<td>EP9800/PSPP</td>
<td>0.38</td>
<td>0.43</td>
<td>2.13</td>
</tr>
<tr>
<td>EP9800/Selected</td>
<td>1.11</td>
<td>1.89</td>
<td>1.03</td>
</tr>
</tbody>
</table>
5.5. Spot Color Reproduction

Spot color, providing attractive color imaging, is widely used in commercial, product and packaging printing. Today, when printing workflow enters the digital era, a suitable digital color-proofing solution should be investigated to meet the needs of spot color printing. Two Epson digital printers (Epson Stylus Pro 4000 and Epson Stylus Pro 9800) combined with commercially available RIPs and their own printer drivers were tested and compared. The quality of gravure spot color reproduction with ink-jet printers was examined in terms of $\Delta E_{ab}^*$. Furthermore, the optimum digital proofing system for spot color printing was been established. The color difference ($\Delta E_{ab}^*$) was calculated using:

$$\Delta E_{ab}^* = \sqrt{(L_{original}^* - L_{sample}^*)^2 + (a_{original}^* - a_{sample}^*)^2(b_{original}^* - b_{sample}^*)^2}$$  \hspace{1cm} (19)

5.5.1. Spot Color Reproduction Procedure

In order to establish a digital proofing system for spot color printing, the digital printers, an Epson Stylus Pro 4000 and an Epson Stylus Pro 9800, were tested for digital proofing with the actual gravure...
production printing substrate and manufacture recommended Epson Premium Semimatte Photo Paper. Different printer control systems, Epson Stylus Pro 4000 printer driver, Epson Stylus Pro 9800 printer driver, GMG ColorProof RIP, and CGS ORIS RIP, all under Microsoft Windows XP, were tested and compared.

5. 5. 1. 1. Custom-made Spot Color Test Charts

The gravure proofer test charts, Blue B-347, Black-392, Red-314, Red-349, Yellow-355, Yellow-357, and Yellow-385 were evaluated. These are typical spot colors used in product gravure printing, in particular for decorative laminates. Each chart consisted of 66 patches of different gray levels, generating a chart with a variety of shades for the color (as shown in Figure 35). The selected colors were printed on the gravure production substrate by a drum cylinder gravure proofing press. Each specific measured area on the individual chart was measured for L’ab’ values five times to characterize measurement error and the average values was computed as original data. According to these original data, the spot color test charts in digital form were generated using Adobe Photoshop CS2, so that these charts could be used for actual digital printing reproduction.

Figure 35. Spot Color Test Chart
5.5.1.2. Spot Color Reproduction with Ink-jet Printers

Spot color printing was controlled by either printer drivers (RGB mode) or commercially available RIPS (CMYK mode). Two substrates were used: the actual gravure production substrate and manufacture recommended Epson Premium Semimatte Photo Paper.

Custom ICC profiles were generated for two substrates for both printers. Based on our experience, custom-made profiles are required to accurately describe the characteristics of a device. Generic profiles shipped by the manufacturer do not characterize a given device very well. For the printer driver, a TC 9.18 chart was printed without color management. Printed charts were then measured with a GretagMacbeth SpectroScanT, using GretagMacbeth Measure Tool 5.0.7 software. The measurement files were used to generate profiles using GretagMacbeth ProfileMaker Pro 5.0.7. The profile settings were as follows: large profile size, neutral gray rendering intent, LOGO classic gamut mapping. The selected spot color test charts were converted from L*a*b* to RGB in Photoshop with absolute colorimetric rendering intent, using created custom profiles. The spot color test charts were then printed via the printer driver. L*a*b* values for each color patch of the chart were measured using the GretagMacbeth SpectroScanT.

For the GMG ColorProof RIP, the ECI2002R CMYK chart was printed without any ink limitation, because a specific full gamut color profile is needed to reproduce spot colors. For the CGS ORIS RIP, the calibrated linearization of the printers was used to output the ECI2002R CMYK chart. Printed charts were then measured with the GretagMacbeth SpectroScanT. The measurement files were used as specific color profiles
for the RIPs. The specific color profiles were then assigned in the corresponding relevant functions for performing spot color matching by using RIP's particular conversion engines. The selected spot color test charts were printed via the GMG ColorProof RIP, and the CGS ORIS RIP. L*a*b* values for each color patch of the chart were measured using the GretagMacbeth SpectroScanT. The detailed information of different print combinations used in the study is listed in Table 33.

Table 33. Print combinations used in the study

<table>
<thead>
<tr>
<th>Printer</th>
<th>Substrate (Media)</th>
<th>Printer control software</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Epson 4000</td>
<td>Gravure production substrate</td>
<td>Epson 4000 printer driver</td>
</tr>
<tr>
<td>2 Epson 4000</td>
<td>Gravure production substrate</td>
<td>GMG ColorProof RIP</td>
</tr>
<tr>
<td>3 Epson 4000</td>
<td>Gravure production substrate</td>
<td>CGS ORIS RIP</td>
</tr>
<tr>
<td>4 Epson 4000</td>
<td>Manufacturer Recommended Proofing Paper</td>
<td>Epson 4000 printer driver</td>
</tr>
<tr>
<td>5 Epson 4000</td>
<td>Manufacturer Recommended Proofing Paper</td>
<td>GMG ColorProof RIP</td>
</tr>
<tr>
<td>6 Epson 4000</td>
<td>Manufacturer Recommended Proofing Paper</td>
<td>CGS ORIS RIP</td>
</tr>
<tr>
<td>7 Epson 9800</td>
<td>Gravure production substrate</td>
<td>Epson 9800 printer driver</td>
</tr>
<tr>
<td>8 Epson 9800</td>
<td>Gravure production substrate</td>
<td>GMG ColorProof RIP</td>
</tr>
<tr>
<td>9 Epson 9800</td>
<td>Gravure production substrate</td>
<td>CGS ORIS RIP</td>
</tr>
<tr>
<td>10 Epson 9800</td>
<td>Manufacturer Recommended Proofing Paper</td>
<td>Epson 9800 printer driver</td>
</tr>
<tr>
<td>11 Epson 9800</td>
<td>Manufacturer Recommended Proofing Paper</td>
<td>GMG ColorProof RIP</td>
</tr>
<tr>
<td>12 Epson 9800</td>
<td>Manufacturer Recommended Proofing Paper</td>
<td>CGS ORIS RIP</td>
</tr>
</tbody>
</table>

5.5.2 Color Gamut Comparison

Figure 36 illustrates the color gamut comparisons for the Epson Stylus Pro 4000 printer driver, GMG ColorProof RIP, and CGS ORIS RIP on the gravure production substrate (with L*a*b* values of original data for reference). As shown in Figure 36, there are some saturated colors that the GMG ColorProof RIP can achieve that the printer driver and CGS
ORIS RIP cannot. The Epson Stylus Pro 4000 printer driver gamut is larger in the higher L* value region, while the CGS ORIS RIP gamut is larger in the lower L* value region. The GMG ColorProof RIP yields wider gamut in the yellow region. It is important to note that some shadow tints in the spot color test charts are out of color gamut of the printer on this substrate, regardless of how it is controlled.

(a) Epson 4000 Printer driver (true color) vs. GMG RIP (black wireframe)
(b) Epson 4000 Printer driver (true color) vs. CGS ORIS RIP (black wireframe)
(c) CGS ORIS RIP (true color) vs. GMG RIP (black wireframe)

Figure 36. Color gamut comparison on gravure production substrate for the Epson Stylus Pro 4000 printer (the L*a*b* values of the printed gravure production ink on the production gravure paper are plotted for reference).

The gamut comparisons on Premium Semimatte Photo Paper for the Epson Stylus Pro 4000 printer driver, GMG ColorProof RIP, and CGS ORIS RIP are shown in Figure 37. The color gamut of the Epson Stylus Pro 4000 printer driver is similar to the color gamut of the CGS ORIS RIP. Compared to the color gamut of the GMG ColorProof RIP, the Epson Stylus Pro 4000 printer driver produces a wider color gamut in the yellow region. The color gamut of the GMG Color Proof RIP is similar to that of the CGS ORIS RIP, with exception of the yellow region. The Epson Stylus Pro 4000 printer driver tends to yield a wider color gamut in terms of total gamut volume (see Table 34 below).
Figure 37. Color gamut comparison on the manufacturer recommended paper for the Epson Stylus Pro 4000 printer

Figure 38 illustrates the color gamut comparisons for the Epson Stylus Pro 9800 printer driver, GMG ColorProof RIP, and CGS ORIS RIP on the gravure production substrate (with L*a*b* values of original data for reference). As shown in Figure 38, the GMG ColorProof RIP and the CGS ORIS RIP yield wider color gamuts in the magenta region, compared to the Epson Stylus Pro 9800 printer driver. The color gamut of the GMG ColorProof RIP is similar to that of the CGS ORIS RIP, except for the yellow region. Some shadow tints in spot color test charts are out of color gamut of the printer on this substrate, no matter what kind of printer control software is used.
The gamut comparisons on Premium Semimatte Photo Paper for the Epson Stylus Pro 9800 printer driver, GMG ColorProof RIP, and CGS ORIS RIP are shown in Figure 39. The color gamut of the GMG ColorProof RIP is similar to that of the CGS ORIS RIP, with the exception of the yellow region. Compared to the color gamut of the GMG ColorProof RIP, the Epson Stylus Pro 9800 printer driver produces a wider color gamut in yellow, magenta, and blue regions. The color gamut of the Epson Stylus Pro 9800 printer driver is similar to that of the CGS ORIS RIP, with the exception of the magenta region.

![Figure 39. Color gamut comparison on the manufacturer recommended paper for Epson Stylus Pro 9800 printer](image)

The comparisons of gamut volumes for gravure production substrate and recommended Epson Premium Semimatte Photo Paper are shown in Table 34 (calculated volume). Obviously, the color gamut with the manufacturer recommended proofing paper is larger than that of the gravure production substrate in terms of gamut volume. The Epson Stylus Pro 9800 printer tends to yield a wider color gamut than that of the Epson Stylus Pro 4000 printer. Overall, the largest gamut volume was found for the Epson Stylus Pro 9800/Premium Semimatte Photo Paper/printer driver combination (with a gamut volume of 753,000), while the Epson Stylus
Pro 4000/gravure production substrate/printer driver combination has the smallest gamut volume (with a gamut volume of 185,000).

Table 34. Gamut volumes comparison for tested substrates

<table>
<thead>
<tr>
<th>Printer</th>
<th>Volume</th>
<th>Decrease [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Recommended Substrate</td>
<td>Gravure Substrate</td>
</tr>
<tr>
<td>Epson 4000 with Printer driver</td>
<td>718,000</td>
<td>185,000</td>
</tr>
<tr>
<td>Epson 4000 with GMG ColorProof RIP</td>
<td>641,000</td>
<td>228,000</td>
</tr>
<tr>
<td>Epson 4000 with CGS ORIS RIP</td>
<td>716,000</td>
<td>194,000</td>
</tr>
<tr>
<td>Epson 9800 with Printer driver</td>
<td>753,000</td>
<td>267,000</td>
</tr>
<tr>
<td>Epson 9800 with GMG ColorProof RIP</td>
<td>702,000</td>
<td>258,000</td>
</tr>
<tr>
<td>Epson 9800 with CGS ORIS RIP</td>
<td>733,000</td>
<td>266,000</td>
</tr>
</tbody>
</table>

5.5.3. ΔE*ab Comparison of Original and Printed L’ab* Values for Spot Color Test Charts

The ΔE*ab values calculated for original and actual printed L’ab* values for each spot color are shown in Table 35. In all cases, absolute colorimetric rendering intent was employed to obtain the best overall absolute color match for each printer/controller/paper combination. The first ΔE*ab value indicates the average ΔE*ab value for each spot color chart. The second ΔE*ab value is the minimum ΔE*ab value, while the third value shows the maximum ΔE*ab value among 66 patches for each spot color.

For the gravure production substrate, both commercially available RIPs provide better color reproduction for the selected spot colors, except for the Yellow-385 spot color (the average ΔE*ab values of selected spot colors are all lower than 4, with the exception of Yellow-385 color). It is interesting to note that the print combination of Epson Stylus Pro 9800 printer printing via its printer driver results in good spot reproduction (the average ΔE*ab values of selected spot colors are all lower than 4). For manufacturer recommended proofing paper, the GMG ColorProof RIP offers better color reproduction for Blue-347, Black-392, Red-314, and Red-
349 spot colors, whereas CGS ORIS RIP has better spot color reproduction in yellow spot colors when combined with the Epson Stylus Pro 9800 printer.

Table 35. Summary of $\Delta E_{ab}^*$ comparison for different print combinations

<table>
<thead>
<tr>
<th>Spot colors</th>
<th>Blue-347</th>
<th>Black-392</th>
<th>Red-314</th>
<th>Red-349</th>
<th>Yellow-355</th>
<th>Yellow-357</th>
<th>Yellow-385</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epson Stylus Pro 4000 printer</td>
<td>5.5, 0.4, 20</td>
<td>3.9, 0.9, 8.3</td>
<td>5.9, 1.0, 24</td>
<td>3.5, 0.4, 8.9</td>
<td>4.4, 0.3, 19</td>
<td>4.0, 0.2, 38</td>
<td>8.2, 0.2, 28</td>
</tr>
<tr>
<td>Printer Driver</td>
<td>2.4, 0.1, 9.9</td>
<td>2.6, 0.2, 11</td>
<td>2.3, 0.0, 9.9</td>
<td>1.4, 0.2, 4.8</td>
<td>1.1, 0.2, 2.7</td>
<td>1.0, 0.2, 2.1</td>
<td>4.1, 0.0, 12</td>
</tr>
<tr>
<td>ORIS RIP</td>
<td>1.4, 0.1, 8.3</td>
<td>1.5, 0.2, 6.9</td>
<td>1.5, 0.3, 7.8</td>
<td>1.1, 0.1, 4.9</td>
<td>1.4, 0.1, 5.3</td>
<td>1.1, 0.1, 2.2</td>
<td>4.5, 0.2, 16</td>
</tr>
<tr>
<td>GMG RIP</td>
<td>2.5, 0.7, 6.0</td>
<td>3.2, 0.4, 13</td>
<td>2.0, 0.6, 6.0</td>
<td>1.8, 0.3, 3.9</td>
<td>1.5, 0.6, 2.8</td>
<td>1.3, 0.2, 2.8</td>
<td>3.5, 0.7, 11</td>
</tr>
<tr>
<td>Epson Stylus Pro 9800 printer</td>
<td>2.5, 0.7, 6.0</td>
<td>3.2, 0.4, 13</td>
<td>2.0, 0.6, 6.0</td>
<td>1.8, 0.3, 3.9</td>
<td>1.5, 0.6, 2.8</td>
<td>1.3, 0.2, 2.8</td>
<td>3.5, 0.7, 11</td>
</tr>
<tr>
<td>Printer Driver</td>
<td>1.8, 0.2, 7.8</td>
<td>1.8, 0.1, 7.8</td>
<td>1.7, 0.3, 8.9</td>
<td>1.7, 0.2, 8.3</td>
<td>1.8, 0.1, 7.9</td>
<td>0.7, 0.2, 1.9</td>
<td>4.7, 0.2, 18</td>
</tr>
</tbody>
</table>

Figures 40 through 46 present line charts of $\Delta E_{ab}^*$ comparisons of original and printed L’a’b’ values for Blue-347, Black-392, Red-314, Red-349, Yellow-355, Yellow-357, and Yellow-385 charts, respectively. The dashed-line represents the reference of 4 $\Delta E$, where 2-5 $\Delta E$ is generally regarded as barely perceptible color differences in high-quality imaging systems.

As shown in Figure 40 and Figure 41, the $\Delta E_{ab}^*$ values of the gravure production substrate (GPS) with the Epson Stylus Pro 4000 and its own printer driver combination (red line) are significantly larger than
those of others. The gravure production substrate tends to have higher \( \Delta E_{ab}^* \) values for the shadow area. The manufacturer recommended proofing paper (MRS), printed via either printer driver or RIPs, has good reproduction capabilities in the selected spot colors in terms of lower \( \Delta E_{ab}^* \) values.

![Figure 40. \( \Delta E_{ab}^* \) comparison of original and printed L\*a\*b\* values for Blue-347](image)

![Figure 41. \( \Delta E_{ab}^* \) comparison of original and printed L\*a\*b\* values for Black-392](image)

For Red-314 and Red-349 spot colors, as shown in Figure 42 and Figure 43, the \( \Delta E_{ab}^* \) values of the gravure production printing substrate with the Epson Stylus Pro 4000 and its own printer driver combination
(red line) are significantly larger than those of others. The gravure production printing substrate tends to have higher $\Delta E_{ab}$ values for the shadow area, with the exception of the Epson Stylus Pro 9800 and its own printer driver combination. The $\Delta E_{ab}$ values of manufacturer recommended proofing paper, conversely, are all lower than 4.

Figure 42. $\Delta E_{ab}$ comparison of original and printed $L^*a^*b^*$ values for Red-314

Figure 43. $\Delta E_{ab}$ comparison of original and printed $L^*a^*b^*$ values for Red-349

Figure 44 and Figure 45 show that the $\Delta E_{ab}$ values of the gravure production substrate with the Epson Stylus Pro 4000 and its own printer driver combination (red line) are significantly larger than those of others.
For the Yellow-355 spot color, the $\Delta E_{ab}^*\!$ values of the gravure production substrate with the Epson Stylus Pro 4000 and its own printer driver combination increase significantly in shadow areas. Other print combinations have better reproduction capability in terms of lower $\Delta E_{ab}^*$ values. For Yellow-357 spot color, the $\Delta E_{ab}^*$ values of tested print combination are all controlled in the range of 0-4, with the exception of the gravure production substrate/Epson Stylus Pro 4000/printer driver combination.

The Yellow-385 spot color, compared to other spot colors, has relatively high $\Delta E_{ab}^*$ values. As shown in Figure 46, the $\Delta E_{ab}^*$ values of tested print combinations increase significantly from the tint of 70%. Overall, printing via the Epson Stylus Pro 9800 tends to have better reproduction capabilities in selected spot colors. Among tested print combinations, the manufacturer recommended substrate/Epson Stylus Pro 9800/CGS ORIS RIP combination (dash-yellow line) has better reproduction capability in Yellow-385 spot color in terms of lower $\Delta E_{ab}^*$ values (in the range of 0.3 - 4.6).

Figure 44. $\Delta E_{ab}^*$ comparison of original and printed L*a*b* values for Yellow-355
Figure 45. ΔE*ab comparison of original and printed L*a*b* values for Yellow-357

Figure 46. ΔE*ab comparison of original and printed L*a*b* values for Yellow-385

Seven different coating formulations were applied on the base paper sheet to mask the roughness and void spaces. The influence of coating compositions on paper properties and the impact of the paper properties on printing properties were studied. It was found that sample 1 (styrene/butadiene latex with large particle size and T_g of -28°) produced a smoother paper surface, smaller porosity and pore size, but a less uniform paper sheet. Sample 4 (styrene/butadiene/acrylonitrile with medium particle size and T_g of 10°) yielded a uniform paper sheet, but rougher paper surface and tends to have larger pore size and porosity. In terms of optical properties, sample 1 tended to have lower brightness and opacity readings. It is interesting to note that there is no significant difference in opacity among the seven types of latex polymer coating formulations.

In terms of ink-paper interaction, all paper samples have similar water absorption curves. However, the slowest penetration can be found in sample 1. Sample 1 has relatively low air permeability and smaller average pore size, which correlates with its slower penetration rate. There are obvious differences between a water ultrasound curve and a toluene ultrasound curve. For all paper samples, less toluene fluid penetrated into paper sheets. DI water penetrated into paper sheets immediately after they came into the contact with water. Sample 1 with has a relatively high print gloss value and lower print mottle in cyan and black, compared to other paper samples. Sample 4, on the other hand, has lower print gloss and lower print mottle in magenta. Tested paper samples have higher
print gloss values in cyan and lower print gloss readings in yellow. The print mottle in yellow of all tested paper is less obvious, compared to other colors. When it comes to color reproduction capability, the color gamuts of tested paper samples are quite similar to each other.

The paper surface/physical properties such as roughness, formation, and air permeability have strong negative relationship with print gloss. However, the correlation between roughness/formation and print mottle is not clear. It was also found that there are no strong relationship between porosity/average pore size and printing properties. However, according to the data, grooved structures and convergent pore geometries seem to decrease print gloss and increase print mottle permanence.

It was found that change of latex in coating formulation from styrene/butadiene to styrene/butadiene/acrylonitrile of varying particle size was not drastic enough to modify physical properties to such extent that they will affect color reproduction.

6.2. The Influence of Coating on the Color Gamut of Ink-jet Paper

The performance of the fumed alumina and fumed silica ink-jet coatings were evaluated. The results have shown that fumed alumina coatings can reach about 30% solids content. Higher solids content allow pigments to run at higher coat weight. Due to less coating water used in the production, less drying is required. Cationic silica with low solids content (18%) encounters problems with drying and it is harder to reach the desired coat weight. Excess coating water penetrates into the base paper and swells fibers, resulting in a rougher surface. Fumed silica coatings are also well known for crack occurrence, most likely because of the low solids content. Therefore, fumed alumina coatings (FA1 and
FA2) produce a smoother and glossier surface than cationic silica coating (FS).

The dye-based printer has better color capability than the pigment-based printer for tested coatings. Tested coatings were more attracted to the negatively charged dye-based ink-jet ink. For fumed alumina coatings, the addition of PVP did not expand the color gamut. Fumed alumina coating (FA1) with PVOH alone has better color capability, when the dye-based printer was used.

Generally, optical density and color gamut improve with increases in the coat weight, since increasing the amount of coating materials improves properties of the coated surface. Some exceptions were observed when the dye-based printer was used. The color gamut expanded with increasing coat weights, except for the PVP enriched fumed alumina coating.

Calendering is usually used to increase the gloss and improve the smoothness of coated papers. Optical density consequently increased with higher degree of calendering. However, calendering can also cause coating layer compression, which in turn affects the density for some colors. Excessive calendering is not desirable when it damages the desired absorbency of the coating layer.


The color gamut of the digital printers is affected by the substrate properties. The digital printer may be designed for a variety of substrates; however, the largest gamut and highest print quality of the device is obtained, when the manufacturer recommended substrate is used. The
device that is capable of reproducing a large gamut of colors on ideal substrates may lose this advantage when using a different substrate.

The results show that the color gamut of proofing papers was larger than that of actual production printing papers printed via a Cerutti rotogravure web press. Proofing on the actual production printing papers with Epson Stylus Pro 4000 printer tends to yield wider color gamuts in yellow area but smaller color gamuts in magenta and red regions. The press gamut is larger in the lower L' value area which the digital printer cannot reach because of low black density. Overall, proofing papers yielded larger color gamuts than actual production printing substrates in terms of gamut volume.

The gamut volume of tested papers significantly correlates with all paper properties. There is a strong positive relationship between gamut volume and formation index, whereas the strong negative relationship was found between gamut volume and roughness. Gamut volume also has a negative relationship with porosity-related characteristics such as pore size, porosity and air permeability. The strong positive relationships were found between gamut volume and brightness/whiteness properties, whereas the relationships strengths between gamut volume and opacity/paper gloss are moderate. That is, paper with low roughness, high formation index, low porosity or air permeability, high brightness or whiteness, and high paper gloss properties exhibits a high gamut volume.

6. 4. Proof-press Color Matching Capability

The quality of proof-press color matching was evaluated in terms of color difference (ΔE*2000) and process consistency. It was confirmed that the color gamuts of the digital proofing systems are wider than for
gravure publication printing. Therefore, the color space can be defined in software at the RIPing stage to optimize the end result, helping to ensure consistency from the proof to the final output. With the aid of color management software, the average $\Delta E^{* \text{ab}}$ values of proof-press color matching are controlled and reach values lower than 1.0. For the Free Sheet, print combinations of Epson Stylus Pro 4000 printer/Selected Proof Paper and Epson Stylus Pro 9800 printer/Pearl Proof Paper provide better proof-press color matching in terms of lower $\Delta E^{* \text{ab}}$ values and a more stable reproduction process. The Epson Stylus Pro 4000 printer with Selected Proof Paper was the best match to the Light Weight Coated Paper (reference press sheet), but its process stability is not ideal. The Epson Stylus Pro 4000 printer/Semimatte Photo Paper and Epson Stylus Pro 9800 printer/Semimatte Photo Paper combinations, on the other hand, produce better proof-press color matching result for Newsprint in terms of lower $\Delta E^{* \text{ab}}$ values, lower paper white $\Delta E$ values, and more stable reproduction processes. The Free Sheet is the hardest substrate to match, compared to other gravure publication printing substrates. Table 36 shows the summary of best proof-press color matching results.

6.5. Spot Color Reproduction

The quality of spot color reproduction with ink-jet printers was studied. A gravure production printing substrate and a manufacturer recommended substrate were tested and compared. It was found that printing either via the printer driver, GMG ColorProof RIP or CGS ORIS RIP, the color gamut of manufacturer recommended proofing paper is significantly larger than that of the gravure production substrate. In the case of the gravure production printing substrate, for the Epson Stylus Pro
Table 36. Summary of best proof-press color matching results

<table>
<thead>
<tr>
<th></th>
<th>Epson 4000/ Pearl</th>
<th>Epson 4000/ PSPP</th>
<th>Epson 4000/ Selected</th>
<th>Epson 9800/ Pearl</th>
<th>Epson 9800/ PSPP</th>
<th>Epson 9800/ Selected</th>
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<tbody>
<tr>
<td>Free Sheet</td>
<td></td>
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</tr>
<tr>
<td>Paper white</td>
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4000 printer, GMG ColorProof RIP yields a larger gamut in the yellow region. For the Epson Stylus Pro 9800 printer, the color gamuts of three printer control systems are similar to one another. The Epson Stylus Pro 9800 printer printing via RIP software tends to yield a wider gamut in the magenta region. In the case of the manufacturer recommended proofing paper, the Epson Stylus Pro 4000 printer driver and CGS ORIS RIP tend to yield wider color gamuts in the yellow region for the Epson Stylus Pro 4000 printer, while the Epson Stylus Pro 9800 printer driver yields a wider color gamut in the magenta region for the Epson Stylus Pro 9800 printer. Controlled by printer driver, GMG ColorProof RIP or CGS ORIS RIP, the Epson Stylus Pro 9800 printer produces more colors than those of the Epson Stylus Pro 4000 printer. The Epson Stylus Pro 9800 printer has a wider color gamut in yellow and red regions, while the Epson Stylus Pro 4000 printer has a wider color gamut in the magenta region. The largest gamut volume was found for the Epson Stylus Pro 9800/manufacturer
recommended proofing paper/printer driver combination (with a gamut volume of 753,000).

For the gravure production substrate, it is not surprising that all tested print combinations have higher ΔE^*ab values in shadow areas. For some shadow tints in spot color test charts, trajectories traversing out of color gamut of the test printer contribute to higher ΔE^*ab values. The gravure production substrate printing via RIP software results in better spot color reproduction in highlight and mid-tone areas. The GMG ColorProof RIP has better spot color reproductions for Blue-347, Black-392, and Yellow-357 spot colors, whereas the CGS ORIS RIP has better spot color reproduction for Yellow-355 and Yellow-385 spot colors. It is interesting to note that the Epson Stylus Pro 9800 printer printing by its own printer driver has good spot color reproduction in Red-314, Red-349, Yellow-355 and Yellow-357 spot colors (the ΔE^*ab values being controlled below 4).

For manufacturer recommended proofing paper, printers printing via RIP software result in better color reproduction. GMG ColorProof RIP has better spot color reproductions for Blue-347, Black-392, Red-314, Red-349 and Yellow-357 spot colors, whereas CGS ORIS RIP has better spot color reproduction for Yellow-355 and Yellow-385 spot colors.

Overall, the usage of third party RIP software results in better spot color reproduction. Users can proof spot colors on the manufacturer recommended proofing paper printing via GMG ColorProof RIP or CGS ORIS RIP if good color-matching is considered crucial. The color match is truly better with GMG ColorProof RIP and CGS ORIS RIP than with printer drivers, even when the calculated color gamut volume with the printer driver is larger. This is likely due to special match features built
into the software by the manufacturers. The best reproduction of selected spot colors can be obtained when the print combination of the Epson Stylus Pro 9800 printer/the manufacturer recommended substrate/CGS ORIS RIP is used.
CHAPTER 7

CONCLUSIONS

Using the right substrate for ink and printing device combination is the key to achieve optimal printability and runnability for a printing process. In this research, the designed coating formulations for LWC paper yielded similar surface properties and color reproduction capability. However, substrates with a rougher surface and larger pore size/porosity tend to decrease print gloss and increase print mottle permanence.

Ink-jet print quality depends on the print medium, especially when it comes to color reproduction capability. Press paper usually loses its advantage, because different sets of inks and devices are used. The largest gamut and highest print quality of the ink-jet printer is obtained when the manufacturer recommended substrate is being used. It was found that papers with low roughness, high formation index, low porosity or air permeability, high brightness or whiteness, and high paper gloss properties exhibit highest gamut volume.

For ink-jet paper, inks and coatings need to be designed together for best performance. Fumed alumina coatings produce a smoother and glossier surface than cationic silica coatings. Cationic silica coating encounters problems with drying and is harder to reach the desired coat weight. Basically, optical density and color gamut improve with increased coat weight, since increasing the amount of coating materials improves uniformity of the coated surface.

Color gamut is one of the crucial properties of digital proofing systems, which determines the range of colors and tonal ranges that digital printers can reproduce. Digital proofing is extremely important for
product and package printing in the case, when the clients wish to have an actual proof “in hand”. Typically, an ink-jet printer has a larger color gamut than a press. Therefore, an ink-jet printer can be utilized to match the color proof to a printing press, as well as to create optimum color prints, such as spot color reproduction for packaging printing. By using the linearization and color matching functions built into the RIP software, the chroma of the ink-jet printer can be reduced to better match the printing press.

As found in this study, with the aid of color management software, the average $\Delta E^*_{2000}$ values of proof-press color matching are controlled and can be maintained at levels lower than 1.0. While color matches improve, inaccuracies due to a mismatch of paper color between the proofer and press become significant (high paper color differences between press paper and proof paper were observed). Although color management control software has function of putting some scum dots on the paper white area of proofing paper for simulating paper white of the press paper, the differences can be noticed. In order to improve the appearance of a color match, paper white Simulation must be well understood and compensated for in the color matching processes.

The usage of third party RIP software also results in better spot color reproduction, due to special match features built into the software by the manufacturers. These two commercially available RIPS provide options to accept recognized Pantone names or create custom spot color libraries. They handle spot colors differently by using their own “secret sauce” spot color matching function. However, both RIPS have feedback mechanism (reproduce spot color back and forth) to do a better job of mapping spot colors. For spot color reproduction, apparently, a large
color gamut is necessary to produce accurate high-saturated spot colors, regardless of which printer control software is used. Large $\Delta E_{ab}^*$ values obtained for some of the colors indicate that these colors cannot be reproduced properly by any of the print combinations. For some high saturated color or shadow tints in spot color test charts, trajectories traversing out of color gamut of the test printer contribute to higher $\Delta E_{ab}^*$ values. Digital printers employing extended color sets, such as Pantone Hexachrome might be required to reproduce these highly saturated colors.
REFERENCES


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APPENDIX

LIST OF PUBLISHED WORK


Paper I to III focus on spot color reproduction with ink-jet printers. Spot colors are widely used in commercial, product or packaging printing. Applicability of spot color reproduction with ink-jet printers can meet the demand in the printing industry, providing unique advantages of shorter run lengths and fast turnaround times. These papers were conducted to examine the quality of spot color reproduction with an ink-jet printer by using a variety of print combinations. The optimum digital proofing system for spot color printing has been established.

Paper IV and paper VI consider the color reproduction of digital proofing from the point of view of paper properties. Since paper is a crucial factor in the digital proofing process, understanding the relationship between paper properties and color gamut can help to predict and control color gamut in the digital proofing system.

Paper V deals with proof-press color matching capability. The proof-press color matching highly depends on the range of color and tone that digital printers can reproduce and also how accurately these color numbers can be manipulated in comparison to printing characteristics. The former is determined by ink-paper interaction of a digital printer and the latter needs the aid of color management. In this paper, the color matching capability was evaluated in terms of color difference ($\Delta E^{*}_{2000}$) and process consistency.
Paper VII evaluates the performance of the ink-jet coatings in terms of roughness, paper gloss, optical density and color gamut. Pigment, as an important component of coating formulations, is the primary determinant of print quality. Commercial pigment samples of fumed silica and fumed alumina with different formulations were tested and compared.

Paper VIII studies the influence of coating compositions on paper properties and the impact of the paper properties on printing properties. Seven kinds of latex polymers were used in coating formulation, and coated in the same condition. The final paper properties such as roughness, formation, pore size, porosity, air permeability, brightness, opacity, and paper gloss were tested. Printed paper samples were collected and printing properties including dynamic penetration, print gloss, and print mottle were evaluated and compared.