Effect of Ink, Substrate, and Target Line Width On Quality of Lines Printed Using a Piezoelectric Inkjet Printer

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Abstract

This study is concerned with the image quality analysis of inkjet lines printed on substrates. ISO 24790 compliant lines are designed and printed on substrate with a drop-on-demand inkjet printer. This study analyzes three print quality attributes of line width, blurriness, and raggedness. The research used cyan, magnetic and standard inks to print the same design on various substrates having differences in gloss and texture. The chosen inks were measured using a rheometer to determine a viscosity range. The effects of substrate structural parameters, such as texture, finishing, weight, and ink type on line quality are discussed. The printed lines were measured using a personalized Image Analysis System (PIAS-II), having a charged couple camera.

Based on the output of print attributes, it was found that substrate has significant effect on all the response variables. The substrate which produced best result is luster for raggedness and linewidth conformity and matte for blurriness. Ink has significant effect on the line width conformity and raggedness whereas there is no significant effect of inks on blurriness. There is no effect of increase in the line width on any of the response variables. A design of experiment methodology was successfully implemented to determine the effect of surface properties of the substrate and the effect of ink properties on print quality.

Introduction

Inkjet printing is attracting the attention of various industries because of its non-impact printing technique. This technology is breaking through into industries, such as packaging, large format printing, decorative printing, and micro-electro-mechanical systems (MEMs). Increase in the use of inkjet technology has

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influenced the rise in new inkjet formulations (Savastano, 2016). The requirement for ink formulations for inkjet printing are that the ink should be able to jet through the micro holes, then settle on the substrate (Kipphan, 2001). The advancement of inkjet technology to make it compatible with specialty inks and substrates has made it an attractive option to new printing markets (Boer, 2015). The use of inkjet printing is expanding because printers have been able to use inkjet to increase their profitability (Gustavson, 2015). With the diversity of requirements by customers there is increase in usage of inkjet in different graphic industries and an increase in variety of substrates and variety of inks. This study seeks to evaluate print quality to yield results that analyze the interaction between inks and substrates in inkjet printing.

Theoretical Basis

The theoretical basis for this research consists of three parts print quality, ISO 24790 standard on which this study was conducted and Design of Experiment (DOE).

Print quality (PQ) is defined as quality of a hardcopy output of a printer. ISO-13660 defined 14 print quality attributes to solve some problems related to PQ. These PQ attributes are blurriness, raggedness, character darkness, contrast, fill, extraneous marks, character fill, character filed, darkness, background haze, graininess, mottle, background, and voids. Among these PQ the line quality attributes are blurriness, raggedness and line width (Briggs, Forrest, Klein, & Tse, 1999).

PQ is usually used for subjective evaluation methods. These is not considered to be a best method as there is no standard governing this process. Objective evaluations on the other hand measures the printed samples without human interference and provide better results. These evaluations give more accurate information than subjective evaluation (Jian et al, 2010)

Line quality is used to assess the line output of printers. The attributes of line quality are line width, raggedness, and blurriness (ISO, 2017). Line quality attributes (defined below) are important to this study.

- Blurriness: “Appearance of being hazy and indistinct in outline, a noticeable transition of darkness from line element to background substrate whose intended transition width is zero” (ISO, 2017, p.2).
- Raggedness: “Appearance of geometric distinction of an edge from its ideal position” (ISO, 2017, p.4)
- Line Width: “Average stroke width, where the stroke width is measured from edge to edge along a line normal to center line of the image element” (ISO, 2017, p.3).

ISO 24790:2017 specifies device-independent image quality attributes, measurement methods, and analytical procedures to describe the quality of output of images from printers (ISO, 2017). The attributes, methods, and procedures rely on measurable properties of printed text and graphic images.

This study relied heavily on Design of Experiments (DOE). This experiment has various parameters that must be discussed, including the process parameters, target parameters (line width), and the variability with respect to the desired line width. DOE is a strategy for planning and analyzing experiments that assists in planning the experiment in order to collect the required data to support statistical analysis. A designed experiment states the research question as hypothesis, which can be tested using statistical methods. DOE encompasses many methodologies for data analysis. This study revolves around factorial design experiment.

Factorial design experiments are used to study the effects of experimental factors on response variables in experiments involving two or more factors. Factorial design estimates the effect of each factor at several levels. There are two kinds of effects which can be investigated using this method. One is the main effect, and the other is the interaction effect. The effect of single factor on a response variable due to variation in the level of that factor is called a main effect. The effect of simultaneously changing the levels of two or more factors on a response variable is called an interaction effect (Montgomery, 2013). Full factorial designs evaluate all the possible combinations of factors and levels. These are the most efficient way to conduct experiments involving multiple factors and they are the only method to determine the effects of interaction (Montgomery, 2013). The motivation for most DOEs is to improve performance.

Design: Test all combinations of factors and levels. A complete set of combinations is called a replicate. It is desirable to run two or more replicates to estimate error. Analysis of variance (ANOVA) is used to accept or reject the null hypothesis (H0). For a factorial design, H0 is the assumption that none of the factors or interactions has an effect on the response variables.

The design chosen for this research is 2 factor, 3 level and two replicates (32 with two replicates). The effects model describes the relationship between factors and effects (Montgomery, 2013).

A test target was developed in compliance with the standard of ISO 24790:2017. Line quality of these printed lines was conducted. The design of experiments approach was carried out to conduct the experiment. This research uses factorial design due to multiple factors being tested and compared at the same time. The experiment was replicated twice to reduce the error.

Literature Review

Two methods are used to assess print quality: objective measurement and subjective print preference. Print quality metrics are objective measures of physical print characteristics while print preference is an overall measure of how customers like a given print. Print quality metrics are well-defined procedures for quantitatively measuring specific print quality features (Dalal et al, 1998). Print quality analysis is one of the primary tools for evaluating print quality and unambiguously communicating the results within an organization and between organizations in the digital print industry. In marketing, print quality can be used in competitive benchmarking and product positioning. In R&D, print quality is used to make repeatable quantitative measurements for analyzing results and provides information for product and process development. In production, print quality analysis ensures efficient measurement and eliminates the manual errors due to operator interpretation (Forrest, 1998).

Line quality is a high-level print quality descriptor which describes the overall quality of lines in printed output (Dalal et al., 1998). Line quality attributes include line location, line width, edge sharpness, and edge raggedness (Briggs et al., 1999). Briggs et al. (1999) reviewed the line quality attributes, definitions, and measurement methods that were expected to become part of the ISO Standard ISO 13660. ISO 13660 has been superseded by ISO 24790. Line quality attributes in ISO 24790 include blurriness, raggedness, and line width (ISO, 2017).

The substrate plays an important role in non-impact printing (NIP) processes such as inkjet. The nature of printability is influenced by the porosity and surface condition of the substrate. Porosity determines the capacity of substrate to absorb ink (Kipphan, 2001). Porosity allows the surface finish of a substrates to be classified as glossy, non-glossy, matte, or luster. Most inkjet inks have low viscosity and low surface tension, so the print quality is highly dependent on paper surface properties (Jurič, Karlović, & Tomić, 2013). Ink-media interactions are the most significant determining print quality (Auslander et al., 1999).

Piezoelectric DOD was chosen because of its ability to provide accurate and variable droplet sizes, to use a wide range of inks even at low temperatures, and to jet the inks without affecting their physical characteristics. The requirements of a printer for this research include the ability to print inks of different viscosities and to leave the physical properties of the ink unaffected by the printing process. Based on these requirements, the Fujifilm Dimatix DMP 3000 printer was selected for the present research. The Dimatix DMP 3000 was specifically designed for printing a wide variety of materials. A unique feature of this printer is that the print heads are replaceable making it possible to use the same printer to conveniently print many inks in a single experiment.

Based on the literature reviewed, the Dimatix printer was found to be well-suited for this research due to its ability to jet a wide range of inks, ability to control factors that could influence print quality, and, finally, to utilize replaceable print heads which facilitate experimentation. The literature also indicated ink viscosity affects print quality, and this conclusion led the researcher to include a range of low viscosity inks in this research. Similarly, the literature led the researcher to conclude that the roughness of a substrate has an effect on print quality. This conclusion led the researcher to include substrates of varying roughness, including a very rough canvas, in the experiment. In the print quality section of the literature review, the importance of line quality is discussed. The International Standards Organization has published a standard that describes a quantitative approach to characterizing print quality based on a target consisting thin lines. This led the researcher to adopt ISO 24790, Measurement of Image Quality Attributes for Hardcopy Output, as the basis for assessing the print quality in this research.

Methodology

The methodology consists of the steps required to conduct preliminary testing, design test target and generate samples for measurement followed by the steps required to analyze these samples and draw conclusions. The methodology is divided in to eight steps which are outlined in the figure shown below (see Figure 1).

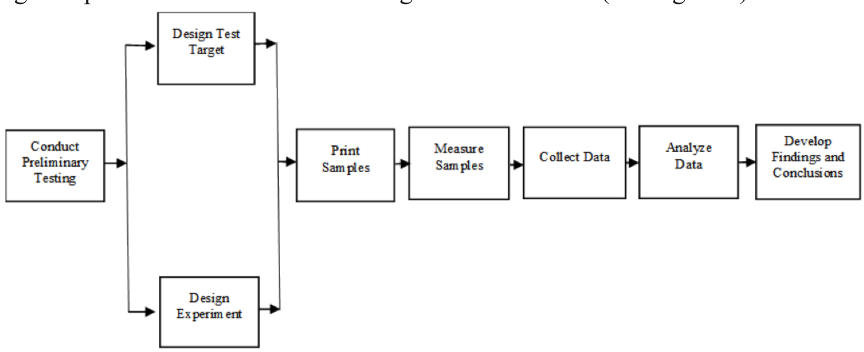

Figure 1. *Steps followed in the experimental procedure*

Preliminary Testing

Dimatix DMP 3000 was used as printer because it could accommodate wide range of jetting fluids and inks, and printheads could be changed. Researcher created and printed sample test targets. The final design was created that could be seen later.

After printing samples, the samples were captured using the PIAS-II (Personal Image Analysis System) instrument manufactured by Quality Engineering Associates (QEA). It has a high-resolution CCD camera and inbuilt IASLab software. With PIAS-II the required information was captured. Based on the data collected test target was finalized which has four-line width of different sizes. These lines were printed at resolution of 800 dpi.

Design of Test Target

The test target designed for this study is based on ISO 24790 and is shown in figure 2. The target lines are 6mm long with a horizontal dotted line at the center of the target. This dotted line was included to provide a guide to measure the lines. The lines were designed to have a 6mm length to accommodate 2mm capture area of the camera and rest 4mm, 2mm at the beginning and 2 mm at the end to avoid any printer artifacts. The spacing between the lines is kept consistent at 2mm so that only one line is in the region of interest. The values of the line widths in the increasing order are 63.5 µm, 95.3 µm, 190.5 µm and 317.5µm.

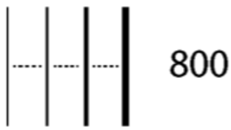

Figure 2. *Test Target Design*

This step consists of four sub-steps which are mentioned below

- Choose the experimental design: A two factor, three-level (32) design was chosen. Each condition was replicated to minimize the experimental error.
- Variable factors: Two factors ink and substrate were chosen for this analysis.
  - The inks used for this research were cyan, magnetic (MICR) and DMP Model (Standard) having viscosities as 3, 8 and 14 cPs respectively. The ink chosen were:
    - Standard Ink: Standard ink designed for the DMP printer by Dimatix.
    - MICR Ink: An ink that includes magnetic particles
- Cyan Ink: Commonly used inkjet ink used in inkjet DOD printers.
  - The Substrates chosen were based on the surface qualities. These substrate surfaces were
    - Luster
    - Matte
    - Canvas
- Controlled factors: Two sets of controlled factors were chosen to minimize experimental error.
  - The first set of factors are associated with the printer. These are:
    - Printhead temperature: effects ink viscosity which would affect the jetting properties on the ink.
    - Platen temperature: effects on drying time of the ink.
    - Waveform pattern: effects the duration for which ink can jet.
    - Nozzle voltage: influences the drop velocity and drop spread.
    - Stand-off distance: affects the time duration of droplets in the air.
    - Sabre angle affects the drop spacing.

    - The second set of factors are associated with test target: These are:
        - The line must fit the 2mm screen of the capture device.
        - There should be a separation between lines of the target.
        - Indicator on the design to measure evenly within the region of interest.
- Response Variables: The response variables chosen for the experiment are the line quality attributes width, blurriness, and raggedness.

Sample Printing

Samples were printed using the Fujifilm Dimatix DMP 3000 printer. These samples were printed with three chosen ink on the three different substrates. The printing was replicated and run twice. Since it was a 32 DOE it has 9 runs in one complete set of randomized experiment. Overall, it had 18 runs and 18 samples were printed.

Measurement

Line quality attributes were measured with the PISA-II. For the 18 samples, 4 different line width were measured for the three response variables.

Data Collection

Excel spreadsheet was used to collect all this data and compiled together. A statistically analysis tool was used to create the randomized data for the data input in the 3rd step.

Data Analysis

The response variables line width, raggedness, and blurriness of each line for each printed sample were analyzed. Data was first observed whether it was valid for analysis and was valid to pursue the experiment. An ANOVA was conducted to test factors and interaction for significance. Finally, main effects due to inks and substrates and interaction effects between them were analyzed. The above-mentioned effects are discussed with respect to each printed line. In total there are 12 (3 attributes x 4-line widths) experimental designs, that were analyzed.

Develop Findings and Conclusions

Upon computation of final analysis, the researcher had:

- Interpreted the meaning of each experiment in isolation.
- Examined within experiment data for relationships and /or trends.
- Examined cross-experiment data for relationships and /or trends.
- Attempted to understand the causes of the findings.
- Drew conclusions from the observations done in the above steps.

Results & Data Analysis

This section discusses how the data was generated and the data analysis for the generated data using the statistical analysis method of DOE. Data obtained from these investigations is summarized in Tables 1 ,2 and 3. The tables are identically organized: the first column in the run order (1-18) of the trials required to test three inks and three substrates with two replicates. For each run, the ink and substrate used are presented in the next two columns. Finally measured results for one response variable are shown in the last four columns.

Table 1 presents data for the first response variable: Line width conformance.

Run Order	Ink	Substrate	Line 1	Line 2	Line 3	Line 4
1	Cyan	Luster	0.098	0.133	0.235	0.348
2	Cyan	Matte	0.113	0.149	0.240	0.369
3	MICR	Matte	0.103	0.128	0.243	0.342
4	Standard	Canvas	0.173	0.170	0.313	0.403
5	Cyan	Matte	0.113	0.141	0.239	0.338
6	MICR	Luster	0.072	0.112	0.240	0.313
7	Standard	Luster	0.107	0.134	0.232	0.363
8	MICR	Matte	0.075	0.133	0.241	0.321
9	Cyan	Canvas	0.104	0.164	0.263	0.374
10	MICR	Canvas	0.103	0.159	0.239	0.338
11	Standard	Matte	0.107	0.142	0.237	0.365
12	Cyan	Canvas	0.136	0.171	0.259	0.387
13	Standard	Matte	0.105	0.140	0.240	0.359
14	MICR	Luster	0.097	0.120	0.220	0.362
15	Standard	Canvas	0.166	0.303	0.337	0.423
16	MICR	Canvas	0.102	0.157	0.243	0.327
17	Cyan	Luster	0.098	0.132	0.233	0.358
18	Standard	Luster	0.106	0.134	0.233	0.360

Table 1. *Line width conformance measurement for all four lines in mm*

Table 2 presents data for the next response variable: Blurriness.

Run Order	Ink	Substrate	Line 1	Line 2	Line 3	Line 4
1	Cyan	Luster	0.099	0.139	0.172	0.166
2	Cyan	Matte	0.076	0.097	0.101	0.099
3	MICR	Matte	0.077	0.073	0.082	0.099
4	Standard	Canvas	0.266	0.248	0.434	0.323
5	Cyan	Matte	0.078	0.085	0.096	0.114
6	MICR	Luster	0.067	0.095	0.135	0.152
7	Standard	Luster	0.101	0.128	0.147	0.165
8	MICR	Matte	0.070	0.075	0.089	0.096
9	Cyan	Canvas	0.188	0.241	0.324	0.293
10	MICR	Canvas	0.175	0.287	0.235	0.299
11	Standard	Matte	0.074	0.075	0.082	0.094
12	Cyan	Canvas	0.213	0.287	0.268	0.303
13	Standard	Matte	0.072	0.078	0.092	0.098
14	MICR	Luster	0.072	0.089	0.117	0.141
15	Standard	Canvas	0.242	0.329	0.344	0.185
16	MICR	Canvas	0.231	0.247	0.327	0.279
17	Cyan	Luster	0.117	0.127	0.185	0.170
18	Standard	Luster	0.102	0.115	0.147	0.158

Table 2. *Blurriness measurement for all four lines in mm*

Finally, Table 3 presents data for the third response variable: Raggedness.

Run Order	Ink	Substrate	Line 1	Line 2	Line 3	Line 4
1	Cyan	Luster	0.001	0.001	0.001	0.003
2	Cyan	Matte	0.004	0.003	0.003	0.003
3	MICR	Matte	0.006	0.002	0.006	0.004
4	Standard	Canvas	0.040	0.029	0.043	0.030
5	Cyan	Matte	0.003	0.003	0.003	0.004
6	MICR	Luster	0.001	0.001	0.001	0.001
7	Standard	Luster	0.001	0.001	0.001	0.001
8	MICR	Matte	0.003	0.003	0.003	0.003
9	Cyan	Canvas	0.023	0.015	0.014	0.018
10	MICR	Canvas	0.014	0.013	0.017	0.015
11	Standard	Matte	0.003	0.003	0.003	0.003
12	Cyan	Canvas	0.019	0.022	0.017	0.019
13	Standard	Matte	0.004	0.003	0.003	0.003
14	MICR	Luster	0.001	0.001	0.001	0.001
15	Standard	Canvas	0.038	0.054	0.034	0.036
16	MICR	Canvas	0.016	0.018	0.020	0.02
17	Cyan	Luster	0.001	0.001	0.005	0.001
18	Standard	Luster	0.001	0.001	0.001	0.001

Table 3. *Raggedness measurement for all four lines in mm.*

The data contained in Table 1,2, and 3 were analyzed as a series of Designed Experiments (DOE). Regression models were created, then checked to confirm their validity DOE was used to assess main effects, interactions, and the significance of the effects observed. The observed value of the response variable will differ from this prediction due to the existence of error. If the experiment is properly controlled, error should result from the cumulative effect of many small uncontrollable factors. Otherwise, the experiment is flawed and some of the effect attributed to the experimental variables is due to the presence of an uncontrolled variable in the experiment.

There are total 12 DOE in this experiment, but only one of the DOE (line width conformance for line 1) is explained here with graphical representation of main effects, discussion of main effects, graphical representation of interactions, discussion of interactions, analysis of significance (ANOVA Table) and discussion of significance. The similar format is used to present the results of rest of the DOE's, based on these observations the conclusions were made.

Ink has a substantial effect on conformance to specified line width as seen in figure 3. In particular, the use of standard ink increases non-conformance, while MICR ink decreases it. Substrate also affects conformance to specified line width. This is primarily because of the luster and canvas substrates. With luster conformity improves, and conformity worsens with canvas.

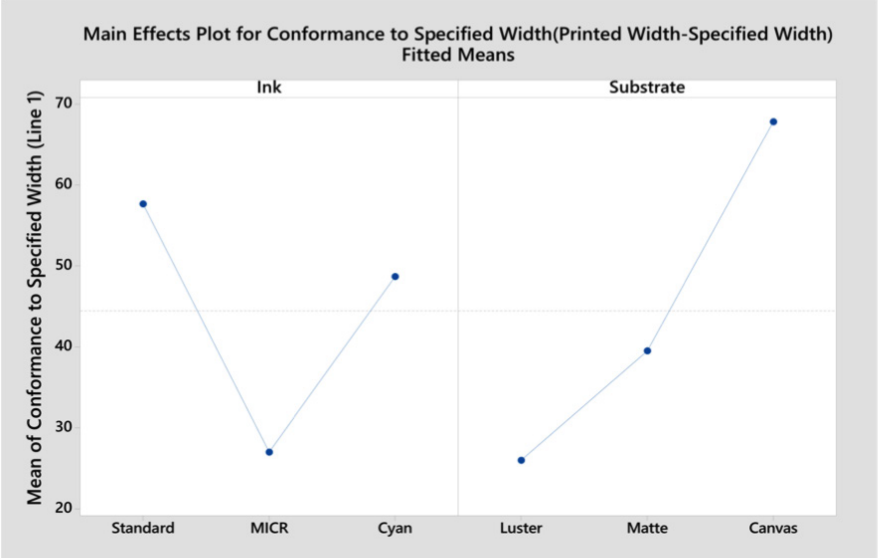

Figure 3. *Main Effects Plot for Printed Width Nonconformance to Line 1 Specified Width (63.5 µm). The Main Effects chart plots observed Line nonconformance (µm) on the vertical axis versus the levels of inks and substrates investigated on the horizontal axis. The dashed line is the mean effect of all inks and all substrates. If the null hypothesis is true, the observed effects will be close to this line. The greater the distance between a factor's effects and the mean line, the greater the likelihood that a real effect is present.*

Figure 4 plots the ink and substrate interaction. Both plots present the same information, so we only need to discuss one of them. Examining the Substrate*Ink plot, note that the lines should all have the same shape of the Substrate Main Effect plot. In fact, only one line (standard ink) has this shape; MICR and cyan are straight lines. This indicates that there is an interaction between ink and substrate. Looking more closely, this is primarily due to the unexpectedly high level of nonconformance observed when canvas is printed with standard ink.

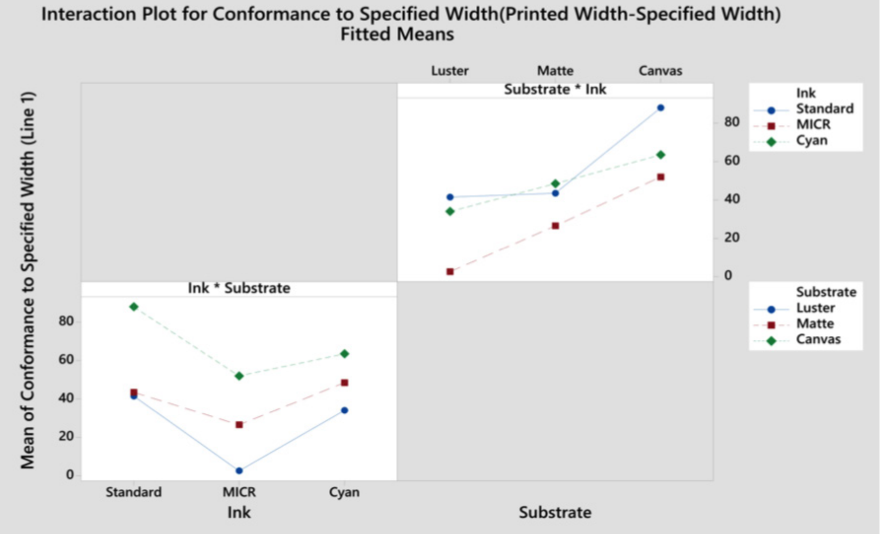

Figure 4. *Interaction Plot for Printed Width Non-Conformance to Line 1 Specified Width. If the null hypothesis is true, the interaction plot will display family of three lines, all having the same shape as the Main Effect plot for the first variable listed in the interaction. If all three lines do not share this shape, an interaction is present.*

To determine if the effects are real and repeatable an analysis of variance was performed. The results of this analysis are summarized in Table 4. As Table 4 demonstrates, the effects of ink and substrate on conformance to specified line width are significant at a level of $p < 0.001$. Based on this, the result suggests a greater than 99.8% confidence that these effects are real and repeatable. Similarly, the effect of the Ink*Substrate interaction is significant at a level of $p = 0.045$. Based on this, the researcher has 95.5% confidence that the interaction effect is real and repeatable.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F value	p value
Model	8	9067.4	96.13%	9067.4	1133.43	27.91	<0.001
Linear	4	8451.9	89.60%	8451.9	2112.97	52.03	<0.001
Ink	2	2981.8	31.61%	2981.8	1490.89	36.71	<0.001
Substrate	2	5470.1	57.99%	5470.1	2735.06	67.35	<0.001
2-Way Interactions	4	615.6	6.53%	615.6	153.89	3.79	0.045
Ink*Substrate	4	615.6	6.53%	615.6	153.89	3.79	0.045
Error	9	365.5	3.87%	365.5	40.61		
Total	17	9432.9	100.00%				

Table 4. *Analysis of Variance for Conformance to Specified Width (Line 1)*

Conclusions

The research hypotheses state that the choice of substrate, ink and target line width (factors) affect line width conformity, raggedness and blurriness (response variables). The effect of each factor on the response variables is discussed below.

Effect of Substrate on response variables

Substrate has a statistically significant effect on all response variables as seen in Table 5.

Performance Metric	Statistical Significance	Best	Middle	Worst
Width Conformance	Significant (99.9% Conf)	Luster	Matte	Canvas
Raggedness	Significant (99.9% Conf)	Luster	Matte	Canvas
Blurriness	Significant (99.9% Conf)	Matte	Luster	Canvas

Table 5. *Effect of Substrate on Performance Metrics*

In the experiment, printed line width was always greater than the target line width. This increase is due to droplet scattering and spread. Rougher surfaces deflect inkjet droplets as they land and scatter the ink over a large area, because droplets impact the substrate at an oblique angle, ink in the droplets spreads and further increases line width. The experiment demonstrated that the best surface for width conformance was the smoothest (luster), matte was in the middle, and the roughest surface(canvas) was worst, this is constant with the effect of the substrate on droplet scattering and spread.

In the experiment the second response variable was raggedness. Raggedness is the measure of roughness of the line edge. The 60% edge threshold (i.e. the boundary where the printed density of the line equals paper density plus 60% of the maximum ink density) is used to define the line edge. A regression line is fitted to the 60% edge, and raggedness is defined as the standard deviation of the residuals from the fitted line. Raggedness is also affected by droplet scattering and spread. Raggedness followed the pattern established for line width conformance which is best surface for this was luster, matte in the middle and canvas was worst.

The last response variable to be analyzed was blurriness. Blurriness is a measure of the sharpness of the transition from paper to ink at the edge of the line. Blurriness is defined as distance between the dynamic threshold of 10% and 90% for the leading and trailing edges of the line. Like line width conformance and raggedness, blurriness is affected by droplet scattering. Unlike these factors, blurriness is also affected by absorption of ink into the substrate. The rough surface of the canvas substrate scatters the droplets widely and produces the highest values for blurriness. Matte and luster substrates scatter droplets less widely than canvas, so absorption plays a larger role in determining the value for blurriness. Luster has a smooth coated surface that absorbs less ink, so small droplets are darker and extent the 10% dynamic threshold. Matte, on the other hand, absorbs ink, reduces the darkness of small dots, and results in less distance between the 90% and 10% thresholds. This, matte exhibit lowest blurriness values, while luster is in the middle.

Effect of Ink on response variables

Ink has a statistically significant effect on width conformance and raggedness this can be seen in Table 6. The effect of ink on blurriness is statistically insignificant.

Performance Metric	Statistical Significance	Best	Middle	Worst
Width Conformance	Significant (99.9% Conf)	MICR	Cyan	Standard Ink
Raggedness	Significant (90.8% to 99.9% Conf)	MICR	Cyan	Standard Ink
Blurriness	Not Significant	NA	NA	NA

Table 6. *Effect of Ink on Performance Metrics*

The effect of ink on inkjet performance depends on the ink's physical properties and the variables controlling its application (droplet volume, print head direction, print head speed, and the number of droplets jetted per second). In the researcher's experiments, application parameters were controlled and kept constant for all the runs. Thus, the effect shown in Table 3 are due to the physical attributes of the inks especially surface tension and viscosity.

Droplet scatter and spread are affected by the viscosity of the ink. Cyan has the lowest viscosity, MICR ink has an intermediate viscosity, and standard ink has highest viscosity. MICR ink performs best in terms of line width conformance. Cyan is in the middle. Due to its low ink viscosity, it is more prone to droplet fragmentation and, hence, to grater deviation between printed and target line widths. Standard ink was the worst performer. Its high viscosity could cause droplet scatter in an uneven manner while retaining relatively large droplet sizes. This would account for greater deviation observed using standard ink

The second response variable, raggedness, behaves similarly to width conformance since both metrics depend on the effects of droplet scatter and spread.

Effect of Line width on response variables

Line width does not appear to have a meaningful effect on width conformance and raggedness as it can be observed in Table 7. The measured values for these response variables exhibit random variation around the mean. Blurriness shows slightly increasing trend as line width increases, this maybe because the maximum ink density in wider lines benefits due to overspray on ink from previous rows of printed dots. As maximum density increases, the distance between the 10% and 90% thresholds increases and makes the edge of the line appear blurrier.

Performance Metric	Line 1	Line 2	Line 3	Line 4
Width Conformance (μm)	44.44	50.14	57.94	47.61
Raggedness (μm)	9.61	9.55	10.16	10.50
Blurriness (μm)	128.89	156.39	187.61	179.67

Table 7. *Effect of line width on Performance Metrics*

In the current research, results were analyzed using designed experiments, analysis of variance, and hypothesis testing. This allowed the researcher to draw statistically valid conclusions concerning the significance of factor effects on response variables. This approach was not observed in most previous studies. In prior studies related to the present research, researchers defined “significance” subjectively or comparatively. In order to compare present and prior conclusions, the researcher applied similar standards of “significance” to his research.

This study can have implications for multiple parties in the graphic arts industry. Perhaps the most far reaching implication is the applying DOE methodology to print quality studies that can lead to clearer understanding of cause and effect. Paper makers and ink suppliers can use this method to improve the printability of their papers and inks. Another implication is that rough surfaces present a high risk of poor performance when printed with inkjet technology. This methodology could be used to help press manufacturers optimize printer designs to generate improved printing results.

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