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Print quality optimization in screen printing by AM and FM screening using Taguchi's Grey Relational Analysis technique

ABSTRACT

This is an experimental and statistical approach to assess the impact of AM and FM screen ruling in screen printing under the condition such as printing of a test target on both coated and uncoated paper with three different types of screen mesh count. The change in print quality according to the screen mesh count are focused here, because the screen mesh count is one of the key elements in screen printing that influences the ink flow through the mesh as well as the excellence of stencil image or halftone dots over the mesh. Under three different screen mesh count, the impact of AM and FM halftone in the print quality on both coated and uncoated paper grades are evaluated in the analysis part. The print quality assessment parameters taken as solid ink density, dot gain, hue error and print contrast at 30%, 50%, & 70% tonal areas of the print. Twelve different combinations of input variables such as coated and uncoated substrate, AM and FM halftone dots, 100 lpi, 120 lpi and 140 lpi screen mesh counts etc. are employed at different print trials. The print quality assessment and ranking of each experiment are done by Taguchi's Grey Relational Analysis, which is a best method to implement in the decision-making process of quality control.

KEY WORDS
Screen printing, AM and FM halftone dots, LPI, solid ink density, dot gain, hue error, print contrast, Taguchi's Grey Relational Analysis

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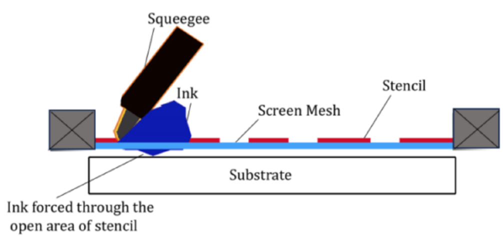
Introduction

The screen printing is one of the versatile printing technologies among the conventional printing method, that utilizes a stencil type image carrier for the printing function. The stencil is attachable over a screen mesh and the printing can be done by forcing ink through the stencil opening by a squeegee on to the substrate. Figure 1 shows the schematic diagram of a screen printing unit.

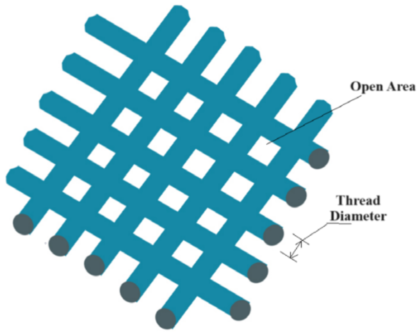


» **Figure 1:** *Schematic diagram of a screen-printing unit*

The printing technique is adaptable to deliver print on a wide range of substrate like paper, paperboard, glass, plastics, metals, ceramics etc. irrespective of their surface textures and shape (Kipphan, 2001). The characteristic of the screen mesh used is a major factor that influences the quality of printed elements in screen printing.

The commonly used screen mesh is nylon, polyester, stainless steel etc. in the industrial purposes. For screen mesh, the screen thread diameter and the open area of mesh is the two major critical parameters that describes the degree of reproducibility of halftone dots via screen printing method.

According to the studies, the fabric with more thread per linear distance is capable to deliver high print quality. At the same time, it should have enough open area to guide the passage of average pigment size of the ink through it to the substrate. Smaller thread diameter builds up finer screen mesh (Novaković et al., 2016). Figure 2 represents the woven structure of screen mesh used for transferring to the substrate.



» **Figure 2:** *The woven structure of screen mesh*

In comparison to other printing methods,screen printing is relatively easy to print on any desired material. However, in order to get the right design with the correct print detail, print resolution, coverage and hand feel, etc., It is necessary to select the right mesh count and ink system for a particular design type. A higher mesh count resulted in high accuracy in design with less ink consumption, good hand feels and good background coverage. On the other hand, a lower mesh count resulted in poor background coverage, poor print detail, and poor print sharpness. There is no significant change in colour speed performance of the printed material with the change in mesh count (Dina, Uddin & Fatema, 2020).

In halftone reproduction, the size of halftone dot should be larger than that of the opening area of the screen mesh used otherwise dot loss or lack of image details in the final print will be the result. This is a common factor applicable to both AM and FM mode of halftone printing via screen printing process. Moreover, the halftone dot reproduction by screen printing is somewhat thoughtful in terms of screen mesh characteristics, accuracy of stencil preparation method, type of stencil used, characteristics of ink, squeegee pressure etc.

In graphic reproduction process, the FM dots are better in highlight and shadow areas and also gives better print results in those areas but fails in middle-tone, while the AM dots are better in middle-tone areas to give the better results (Poljacek Mahovic et al., 2005). The material that plans to print is equally important as the specifics of our screen print process. The composition, structure and characteristics of the printed items, along with the composition, viscosity and other properties of ink, all contribute to the quality of the screen printed matter (Cazac et al., 2018).

The Taguchi method is laid down by Genichi Taguchi, a Japanese engineer in 1950's and acts as a better concept for the improvement of quality of product and process involved in a manufacturing process. Taguchi's concept of robust design indicates the design which gives the production of goods with less sensitive responses towards the factors that causes variability in the manufacturing process (Kumar, 2020).

The Taguchi method is a better approach to apply in the industrial production activities that will entirely modify the outlook of production process on quality improvement and error free performance aspects (Roy, 2010).

The Grey Relational Analysis Concept is laid down by Deng Julong in 1982. This is a statistical approach that acts as a reliable decision-making tool in multiple criteria-based decision-making situations in various industrial based applications. Taguchi's GRA approach is useful methodology in the quality control process (Kumar & Baral, 2023).

The print quality assessment is probable with the quantitative analysis of dot gain, dot area, print contrast, hue error etc. The dot gain and dot area values that monitors the dot reproduction accuracy of the graphic reproduction at the final print. The print contrast value represents the accuracy of reproducing shadow details on the final print. The hue error that represents the percentage of change in actual hue in the final print (Dharavath, Bensel & Gaddam, 2005).

This research is an experimental study to find the influence of factors such as screen mesh ruling, AM and FM halftone dots, coated and uncoated paper grades etc. on the print quality of screen printing.

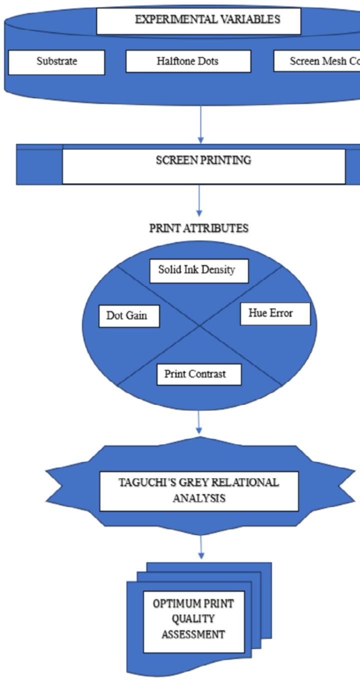
The attainment of best quality is assessed by Taguchi's Grey Relational Analysis method.

Methods

The research was conducted by printing an ideal grey scale image consisting of both AM and FM dots onto both coated and uncoated paper by screen printing method. Three different screen mesh ruling such as 100 lpi, 120 lpi and 140 lpi (lines per inch) were used to form the stencils.

The stencils consisting of halftone grey scale were fixed in flatbed semiautomatic screen printing machine:ATOM 1520, APL Machinery Pvt.Ltd. and prints were obtained on both coated and uncoated papers. The printed samples were subjected to the visual inspection by Digital Microscope (LEICA, S8APO) and the quantitative optical property measurement by Spectro-Densitometer (such as X-Rite Spectro Eye & TECHKON GmbH Spectro Dens).

The 30%, 50% and & 70% tonal areas (representing highlight area, middle tone area and shadow area respectively) were considered for quantitative assessment of the quality. The Solid Ink Density, Dot Gain, Hue Error and Print Contrast etc. of these tonal values were analysed with Taguchi's Grey Relational Analysis. The sequential flow of research work is shown in the illustration Figure 3.



» **Figure 3:** *Work Flow*

The Table 1 represents the list of input variables taken for the process and the various parameters of the prints considered for assessing the print quality. These were taken as the key elements in the Taguchi's Grey Relational Analysis of this research work. Table 2 represents necessary equations used for assessment of print quality using Taguchi's Grey Relational Analysis technique.

Table 1

Elements taken for Taguchi's Grey Relational Analysis

No.	Input variables of experiment	Parameters
1	Coated Paper, 100 lpi Mesh, AM Dot	
2	Coated Paper, 120 lpi Mesh, AM Dot	
3	Coated Paper, 140 lpi Mesh, AM Dot	Solid Ink
4	Coated Paper, 100 lpi Mesh, FM Dot	Density
5	Coated Paper, 120 lpi Mesh, FM Dot	
6	Coated Paper, 140 lpi Mesh, FM Dot	Dot Gain
7	Uncoated Paper, 100 lpi Mesh, AM Dot	
8	Uncoated Paper, 120 lpi Mesh, AM Dot	Hue Error
9	Uncoated Paper, 140 lpi Mesh, AM Dot	
10	Uncoated Paper, 100 lpi Mesh, FM Dot	Print Contrast
11	Uncoated Paper, 120 lpi Mesh, FM Dot	
12	Uncoated Paper, 140 lpi Mesh, FM Dot	

Table 2

Equations used for assessment of print quality

Normalization of Performance Index Data,

For beneficial attributes (higher is better),

$$Xi^{*}(k) = \frac{Xi(k) - minXi(k)}{Xi(k) - Xi(k)} \quad (1)$$

For non-beneficial attributes (lower is better),

$$Xi^{*}(k) = \frac{max\,Xi(k) - Xi(k)}{Xi(k) - Xi(k)} \quad (2)$$

where,

$Xi^{*}(k)$ = Normalized value of i^{th} data of 'k' responses.

Xi(k) = Actual value of i^{th} data of 'k' responses.

min Xi(k) = Lowest value of Xi(k) for 'k' responses.

max Xi(k) = Highest value of Xi(k) for 'k' responses.

Deviation Sequence,

$$\Delta i(k) = X_0^{m}(k) - Xi^{*}(k) \quad (3)$$

where,

Δi(k) = Deviation sequence of i^{th} data for 'k' responses.

$X_0^{m}(k)$ = Maximum value among the Xi(k) elements of 'k' responses.

$Xi^{*}(k)$ = Normalized value of performance index of 'k' responses.

Grey Relational Co-efficient,

$$\xi i(k) = \frac{\Delta\min + \xi\,\Delta\max}{\Delta\, i(k) + \xi\,\Delta\max} \quad (4)$$

where,

ξi(k) = Grey Relational Co-efficient of i^{th} data for 'k' responses.

Δmin = Minimum value obtained from Deviation sequence.

Δmax = Maximum value obtained from Deviation sequence.

Δi(k) = Deviation sequence of i^{th} data for 'k' responses.

Dynamic Distinguished Coefficient (ξ) = 0-1(For multiple decision-making criteria, the value can take as 0.5).

Grey Relational Grade,

$$\Upsilon i = \frac{1}{n}\sum_{k=1}^{n} \xi i(k) \quad (5)$$

where,

ϒi = Grey Relational Grade of i^{th} data for 'k' responses.

n = Number of data responses

ξi(k) = Grey Relational Co-efficient of i^{th} data for 'k' responses

Results

The Figure 4 to Figure 8 graphically represents the output responses such as: dot area, dot gain, hue error, print contrast and solid ink densities of reproduced image against the target dot percentage that ranging from 5% to 100% dot coverage with an incremental step of 5%. The Figure 4 and Figure 5 shows the Dot Area curve and followed by Dot Gain curve respectively. These curves show that, the dot area of printed sample is comparatively higher for FM dots on uncoated paper with 100 lpi mesh count. This represents the higher dot gain associated with uncoated paper with lower mesh count and FM dot combination in screen printing process.

Meanwhile, the AM dot print on coated paper with 140 lpi mesh count gives a better dot area reproduction when comparing to all other cases. This implies that, higher the mesh count lesser will be the dot gain and also the AM dots with smooth textured substrate also facilitates the attainment of optimum dot gain. Lower mesh count with FM dots is a poor choice in screen printing. Because the larger mesh openings of screen at lower mesh count will facilitate considerable loss of FM dot details on the stencil over the mesh and there will be high dot gain issues in the final reproduction due to larger openings.

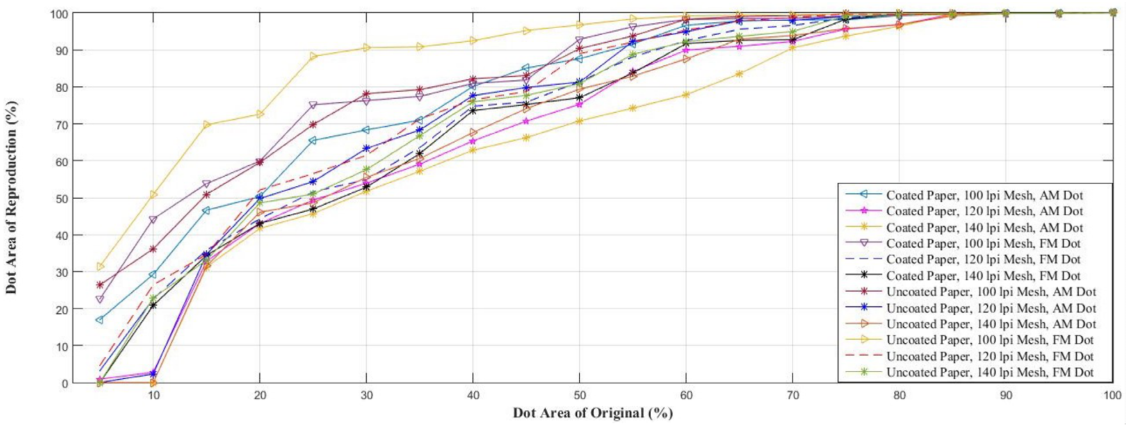
Also, the uncoated paper facilitates the unpredictable dot gain due to the undesirable ink absorption on to its porous structure and unevenness of the surfaces. Also there is a chance of optical dot gain due to the light scattering effects from the paper surface. It has been observed that at highlight areas up to 15%, there is loss of dots with 140 lpi and 120 lpi mesh count in case of AM dots. This may be due to the inability of the screen mesh to carry the finer sized AM dots at those highlight areas.

Meanwhile the FM dots performed in a better way at the highlight and shadow areas only in the case of higher mesh count. The Figure 6 shows the graphical representation of Hue Error of print.

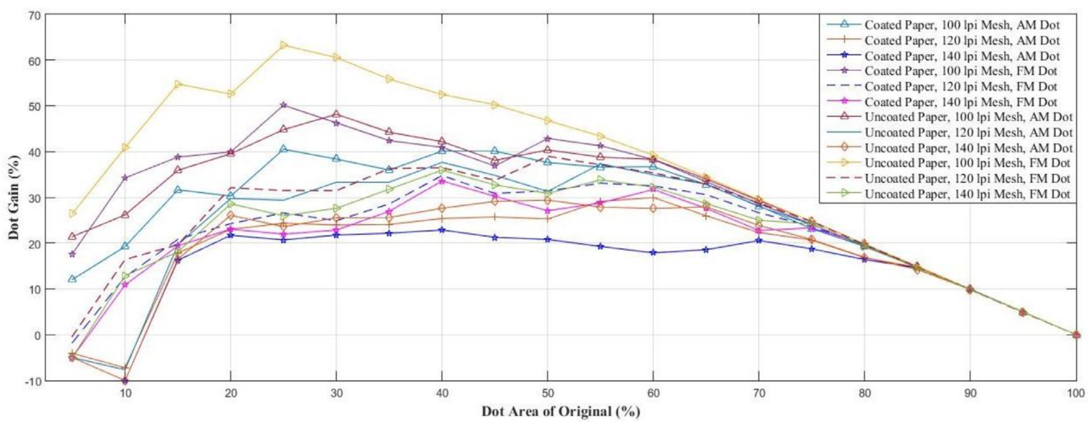
The overall Hue error is minimum for prints on coated paper with AM dots using 140 lpi screen mesh. The Hue Error remains constant till the 40% Dot Area. The higher Hue Error value is obtained for uncoated paper especially at the middle tone areas. However, the hue error is the indicator of purity of ink in the print and it is influenced by press conditions, and the spectral behaviour of the ink and substrate used.

The Figure 7 shows the Print Contrast curve, in which, the best print contrast is obtained for AM dot print on coated paper with 140 lpi mesh count and the lowest print contrast is found on the FM dot print on uncoated paper with 100 lpi mesh count. The print contrast represents the accuracy of tonal reproduction in contrast with the shadow details. The higher mesh count of screen with AM dot and smooth textured substrate improves the print contrast of screen printing. The Print Contrast is near about zero beyond 85% Dot Area in all the cases.

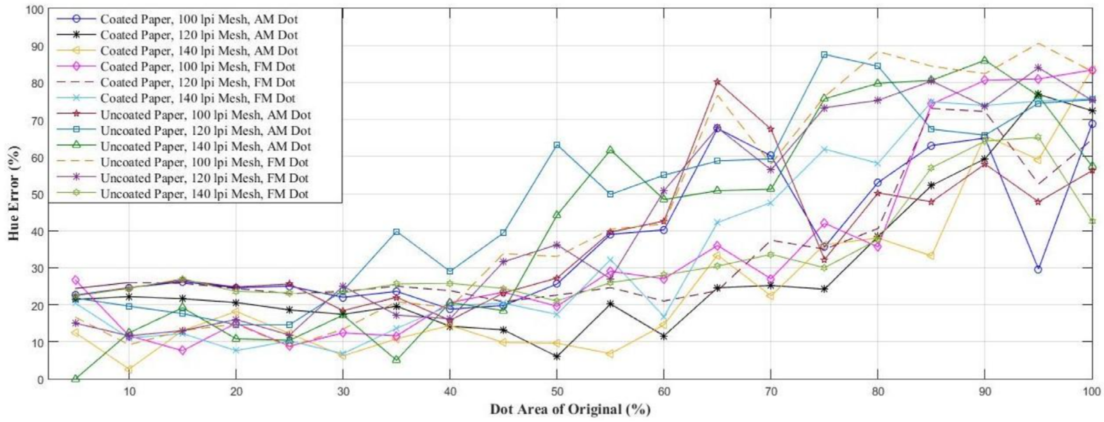
Figure 8 is a bar graph that shows the solid ink densities reproduced on the print, among which, the more vibrant colour of solid ink coverage is obtained for FM dots on coated paper with low mesh count. It was also observed that lower the screen mesh count, higher will be the ink deposit on the substrate.



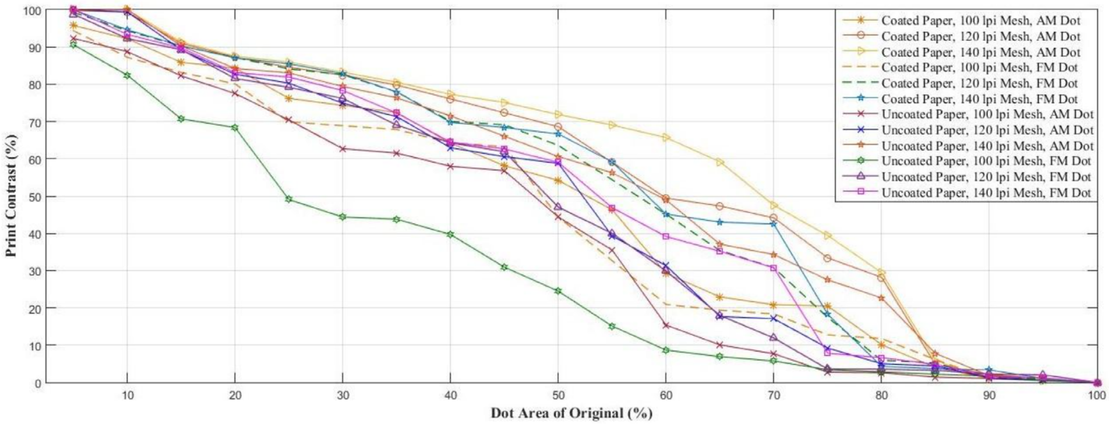
» **Figure 4:** *Tonal Reproduction Curve for Dot area*



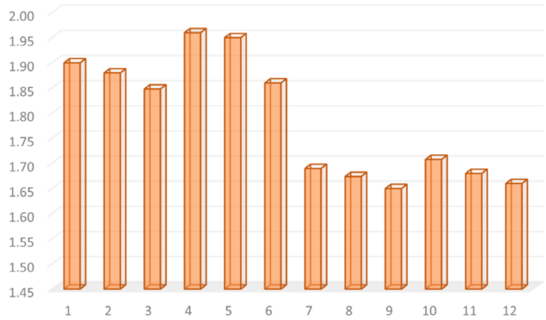
» **Figure 5:** *Variation in Dot Gain with respect to percentage Dot Area of the original*



» **Figure 6:** *Variation in Hue Error with percentage Dot Area of the original*



» **Figure 7:** *Variation in Print Contrast with reference to percentage Dot Area of the original*



» **Figure 8:** *The solid ink density of various prints of different combination of Mesh and Substrate*

The Taguchi's Grey Relational Analysis is carried out in various stages such as Normalization of data (shown in Table 3), calculation of Deviation sequence (shown in Table 4), calculation of Grey Relational Coefficient (shown in Table 5).

Based on quality assessment parameters such as SID, Dot Gain, Hue Error and Print Contrast, each experimental approaches are ranked (vide shown in Table 6 to Table 15) and among which the highest GRA score indicates the best print quality.

Discussions

The GRA index score for SID is shown in Table 6 indicates that the coated grade paper has the ability to reproduce better solid ink density by screen printing using different types of dots and mesh count than that of uncoated paper. The smooth surface texture of the coated paper enhances the excellent reproduction of solid ink density in all cases. But for uncoated paper, the irregular and matt surface texture diminishes such effects due to the uneven distribution of ink over the uncoated surface as well the undesirable light scattering effects from the paper.

At lower screen mesh count, the ink deposition on the substrate will be more in screen printing than that of higher screen mesh count. Here the 100 lpi screen mesh count can reproduce better solid ink densities than that of 140 lpi mesh count. The lower the screen meshes count more will be the mesh open areas, so the ink flow will be more and the heavier ink deposition will be the result. Also, at solid ink density deposition, the printed sample with FM dots offers higher optical densities than that of AM dots as shown in Table 6. The AM dot with low mesh count is also capable to deliver heavy ink deposition, but the FM dots are comparatively capable to give more vibrant colours than AM at solid densities.

Table 3
Normalised Data of Performance Index

Expe-riment No.	Solid Ink Density	Dot Gain at 30%	Dot Gain at 50%	Dot Gain at 70%	Hue Error at 30%	Hue Error at 50%	Hue Error at 70%	Print Contrast at 30%	Print Contrast at 50%	Print Contrast at 70%
1	0.81	0.57	0.35	0.16	0.16	0.66	0.16	0.77	0.63	0.36
2	0.74	0.94	0.83	0.81	0.40	1.00	0.94	0.98	0.93	0.92
3	0.64	1.00	1.00	1.00	1.00	0.94	1.00	1.00	1.00	1.00
4	1.00	0.37	0.15	0.10	0.67	0.76	0.90	0.63	0.42	0.30
5	0.97	0.92	0.59	0.32	0.07	0.71	0.67	0.98	0.83	0.60
6	0.68	0.97	0.76	0.75	0.97	0.80	0.44	0.99	0.89	0.88
7	0.13	0.32	0.25	0.02	0.35	0.63	0.00	0.47	0.42	0.05
8	0.08	0.70	0.60	0.17	0.06	0.00	0.18	0.79	0.72	0.27
9	0.00	0.90	0.67	0.63	0.41	0.33	0.36	0.90	0.76	0.68
10	0.19	0.00	0.00	0.00	0.62	0.53	0.21	0.00	0.00	0.00
11	0.10	0.75	0.30	0.08	0.00	0.47	0.24	0.82	0.48	0.15
12	0.03	0.85	0.61	0.50	0.10	0.74	0.75	0.87	0.73	0.60

Table 4
Deviation Sequence

Exper-iment No.	Solid Ink Density	Dot Gain at 30%	Dot Gain at 50%	Dot Gain at 70%	Hue Error at 30%	Hue Error at 50%	Hue Error at 70%	Print Contrast at 30%	Print Contrast at 50%	Print Contrast at 70%
1	0.19	0.43	0.65	0.84	0.84	0.34	0.84	0.23	0.37	0.64
2	0.26	0.06	0.17	0.19	0.60	0.00	0.06	0.02	0.07	0.08
3	0.36	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00
4	0.00	0.63	0.85	0.90	0.33	0.24	0.10	0.37	0.58	0.70
5	0.03	0.08	0.41	0.68	0.93	0.29	0.33	0.02	0.17	0.40
6	0.32	0.03	0.24	0.25	0.03	0.20	0.56	0.01	0.11	0.12
7	0.87	0.68	0.75	0.98	0.65	0.37	1.00	0.53	0.58	0.95
8	0.92	0.30	0.40	0.83	0.94	1.00	0.82	0.21	0.28	0.73
9	1.00	0.10	0.33	0.37	0.59	0.67	0.64	0.10	0.24	0.32
10	0.81	1.00	1.00	1.00	0.38	0.47	0.79	1.00	1.00	1.00
11	0.90	0.25	0.70	0.92	1.00	0.53	0.76	0.18	0.52	0.85
12	0.97	0.15	0.39	0.50	0.90	0.26	0.25	0.13	0.27	0.40

Table 5 (part 1)
Grey Relational Coefficient

Exper-iment No.	Solid Ink Density	Dot Gain at 30%	Dot Gain at 50%	Dot Gain at 70%	Hue Error at 30%	Hue Error at 50%	Hue Error at 70%	Print Contrast at 30%	Print Contrast at 50%	Print Contrast at 70%
1	0.72	0.54	0.44	0.37	0.37	0.59	0.37	0.69	0.57	0.44
2	0.66	0.90	0.74	0.72	0.46	1.00	0.89	0.96	0.88	0.86
3	0.58	1.00	1.00	1.00	1.00	0.89	1.00	1.00	1.00	1.00
4	1.00	0.44	0.37	0.36	0.60	0.68	0.83	0.58	0.46	0.42
5	0.94	0.86	0.55	0.42	0.35	0.63	0.60	0.97	0.74	0.56
6	0.61	0.95	0.67	0.67	0.94	0.72	0.47	0.98	0.82	0.81
7	0.36	0.42	0.40	0.34	0.44	0.57	0.33	0.49	0.46	0.34
8	0.35	0.63	0.55	0.38	0.35	0.33	0.38	0.70	0.64	0.41
9	0.33	0.84	0.60	0.58	0.46	0.43	0.44	0.84	0.68	0.61

Table 5 (part 2)

Grey Relational Coefficient

Exper-iment No.	Solid Ink Density	Dot Gain at 30%	Dot Gain at 50%	Dot Gain at 70%	Hue Error at 30%	Hue Error at 50%	Hue Error at 70%	Print Contrast at 30%	Print Contrast at 50%	Print Contrast at 70%
10	0.38	0.33	0.33	0.33	0.57	0.51	0.39	0.33	0.33	0.33
11	0.36	0.67	0.42	0.35	0.33	0.49	0.40	0.73	0.49	0.37
12	0.34	0.77	0.56	0.50	0.36	0.66	0.67	0.80	0.65	0.55

Table 6

The Grey Relational Grade and Ranking for SID

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 100 lpi Mesh, FM Dot	1	4
2	Coated Paper, 120 lpi Mesh, FM Dot	0.939394	5
3	Coated Paper, 100 lpi Mesh, AM Dot	0.72093	1
4	Coated Paper, 120 lpi Mesh, AM Dot	0.659574	2
5	Coated Paper, 140 lpi Mesh, FM Dot	0.607843	6
6	Coated Paper, 140 lpi Mesh, AM Dot	0.580524	3
7	Uncoated Paper, 100 lpi Mesh, FM Dot	0.380835	10
8	Uncoated Paper, 100 lpi Mesh, AM Dot	0.364706	7
9	Uncoated Paper, 120 lpi Mesh, FM Dot	0.356322	11
10	Uncoated Paper, 120 lpi Mesh, AM Dot	0.351474	8
11	Uncoated Paper, 140 lpi Mesh, FM Dot	0.340659	12
12	Uncoated Paper, 140 lpi Mesh, AM Dot	0.333333	9

Table 7

The Grey Relational Grade and Ranking for 30% Dot Gain

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 140 lpi Mesh, AM Dot	1	3
2	Coated Paper, 140 lpi Mesh, FM Dot	0.945868	6
3	Coated Paper, 120 lpi Mesh, AM Dot	0.898934	2
4	Coated Paper, 120 lpi Mesh, FM Dot	0.860275	5
5	Uncoated Paper, 140 lpi Mesh, AM Dot	0.836995	9
6	Uncoated Paper, 140 lpi Mesh, FM Dot	0.768237	12
7	Uncoated Paper, 120 lpi Mesh, FM Dot	0.666259	11
8	Uncoated Paper, 120 lpi Mesh, AM Dot	0.626478	8
9	Coated Paper, 100 lpi Mesh, AM Dot	0.538942	1
10	Coated Paper, 100 lpi Mesh, FM Dot	0.441564	4
11	Uncoated Paper, 100 lpi Mesh, AM Dot	0.423592	7
12	Uncoated Paper, 100 lpi Mesh, FM Dot	0.333333	10

Table 8

The Grey Relational Grade and Ranking for 50% Dot Gain

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 140 lpi Mesh, AM Dot	1	3
2	Coated Paper, 120 lpi Mesh, AM Dot	0.743286	2
3	Coated Paper, 140 lpi Mesh, FM Dot	0.674287	6
4	Uncoated Paper, 140 lpi Mesh, AM Dot	0.60192	9
5	Uncoated Paper, 140 lpi Mesh, FM Dot	0.563111	12
6	Uncoated Paper, 120 lpi Mesh, AM Dot	0.552834	8
7	Coated Paper, 120 lpi Mesh, FM Dot	0.550254	5
8	Coated Paper, 100 lpi Mesh, AM Dot	0.43576	1
9	Uncoated Paper, 120 lpi Mesh, FM Dot	0.416692	11
10	Uncoated Paper, 100 lpi Mesh, AM Dot	0.398931	7
11	Coated Paper, 100 lpi Mesh, FM Dot	0.370185	4
12	Uncoated Paper, 100 lpi Mesh, FM Dot	0.333333	10

Table 9

The Grey Relational Grade and Ranking for 70% Dot Gain

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 140 lpi Mesh, AM Dot	1	3
2	Coated Paper, 120 lpi Mesh, AM Dot	0.720117	2
3	Coated Paper, 140 lpi Mesh, FM Dot	0.669859	6
4	Uncoated Paper, 140 lpi Mesh, AM Dot	0.575611	9
5	Uncoated Paper, 140 lpi Mesh, FM Dot	0.50187	12
6	Coated Paper, 120 lpi Mesh, FM Dot	0.424586	5
7	Uncoated Paper, 120 lpi Mesh, AM Dot	0.375753	8
8	Coated Paper, 100 lpi Mesh, AM Dot	0.372034	1
9	Coated Paper, 100 lpi Mesh, FM Dot	0.358086	4
10	Uncoated Paper, 120 lpi Mesh, FM Dot	0.352903	11
11	Uncoated Paper, 100 lpi Mesh, AM Dot	0.338944	7
12	Uncoated Paper, 100 lpi Mesh, FM Dot	0.333333	10

Table 10

The Grey Relational Grade and Ranking for 30% Hue Error

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 140 lpi Mesh, AM Dot	1	3
2	Coated Paper, 140 lpi Mesh, FM Dot	0.94	6
3	Coated Paper, 100 lpi Mesh, FM Dot	0.602564	4
4	Uncoated Paper, 100 lpi Mesh, FM Dot	0.566265	10
5	Uncoated Paper, 140 lpi Mesh, AM Dot	0.460784	9
6	Coated Paper, 120 lpi Mesh, AM Dot	0.456311	2
7	Uncoated Paper, 100 lpi Mesh, AM Dot	0.435185	7
8	Coated Paper, 100 lpi Mesh, AM Dot	0.373016	1
9	Uncoated Paper, 140 lpi Mesh, FM Dot	0.356061	12
10	Coated Paper, 120 lpi Mesh, FM Dot	0.350746	5
11	Uncoated Paper, 120 lpi Mesh, AM Dot	0.348148	8
12	Uncoated Paper, 120 lpi Mesh, FM Dot	0.333333	11

Table 11

The Grey Relational Grade and Ranking for 50% Hue Error

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 120 lpi Mesh, AM Dot	1	2
2	Coated Paper, 140 lpi Mesh, AM Dot	0.888199	3
3	Coated Paper, 140 lpi Mesh, FM Dot	0.715	6
4	Coated Paper, 100 lpi Mesh, FM Dot	0.677725	4
5	Uncoated Paper, 140 lpi Mesh, FM Dot	0.655963	12
6	Coated Paper, 120 lpi Mesh, FM Dot	0.632743	5
7	Coated Paper, 100 lpi Mesh, AM Dot	0.593361	1
8	Uncoated Paper, 100 lpi Mesh, AM Dot	0.574297	7
9	Uncoated Paper, 100 lpi Mesh, FM Dot	0.514388	10
10	Uncoated Paper, 120 lpi Mesh, FM Dot	0.486395	11
11	Uncoated Paper, 140 lpi Mesh, AM Dot	0.428144	9
12	Uncoated Paper, 120 lpi Mesh, AM Dot	0.333333	8

Table 12 (part 1)

The Grey Relational Grade and Ranking for 70% Hue Error

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 140 lpi Mesh, AM Dot	1	3
2	Coated Paper, 120 lpi Mesh, AM Dot	0.889328	2

Table 12 (part 2)

The Grey Relational Grade and Ranking for 70% Hue Error

Rank	Experimental variables	Grey Relational Grade	Experiment No.
3	Coated Paper, 100 lpi Mesh, FM Dot	0.830258	4
4	Uncoated Paper, 140 lpi Mesh, FM Dot	0.667656	12
5	Coated Paper, 120 lpi Mesh, FM Dot	0.6	5
6	Coated Paper, 140 lpi Mesh, FM Dot	0.471698	6
7	Uncoated Paper, 140 lpi Mesh, AM Dot	0.438596	9
8	Uncoated Paper, 120 lpi Mesh, FM Dot	0.39823	11
9	Uncoated Paper, 100 lpi Mesh, FM Dot	0.387263	10
10	Uncoated Paper, 120 lpi Mesh, AM Dot	0.378151	8
11	Coated Paper, 100 lpi Mesh, AM Dot	0.373134	1
12	Uncoated Paper, 100 lpi Mesh, AM Dot	0.333333	7

Table 13

The Grey Relational Grade and Ranking for 30% Print Contrast

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 140 lpi Mesh, AM Dot	1	3
2	Coated Paper, 140 lpi Mesh, FM Dot	0.97837	6
3	Coated Paper, 120 lpi Mesh, FM Dot	0.967088	5
4	Coated Paper, 120 lpi Mesh, AM Dot	0.961473	2
5	Uncoated Paper, 140 lpi Mesh, AM Dot	0.835247	9
6	Uncoated Paper, 140 lpi Mesh, FM Dot	0.798154	12
7	Uncoated Paper, 120 lpi Mesh, FM Dot	0.734116	11
8	Uncoated Paper, 120 lpi Mesh, AM Dot	0.700236	8
9	Coated Paper, 100 lpi Mesh, AM Dot	0.685541	1
10	Coated Paper, 100 lpi Mesh, FM Dot	0.575144	4
11	Uncoated Paper, 100 lpi Mesh, AM Dot	0.486471	7
12	Uncoated Paper, 100 lpi Mesh, FM Dot	0.333333	10

Table 14 (part 1)

The Grey Relational Grade and Ranking for 50% Print Contrast

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 140 lpi Mesh, AM Dot	1	3
2	Coated Paper, 120 lpi Mesh, AM Dot	0.879562	2
3	Coated Paper, 140 lpi Mesh, FM Dot	0.820181	6

Table 14 (part 2)

The Grey Relational Grade and Ranking for 50% Print Contrast

Rank	Experimental variables	Grey Relational Grade	Experiment No.
4	Coated Paper, 120 lpi Mesh, FM Dot	0.741233	5
5	Uncoated Paper, 140 lpi Mesh, AM Dot	0.677953	9
6	Uncoated Paper, 140 lpi Mesh, FM Dot	0.648809	12
7	Uncoated Paper, 120 lpi Mesh, AM Dot	0.644314	8
8	Coated Paper, 100 lpi Mesh, AM Dot	0.573083	1
9	Uncoated Paper, 120 lpi Mesh, FM Dot	0.488219	11
10	Coated Paper, 100 lpi Mesh, FM Dot	0.463068	4
11	Uncoated Paper, 100 lpi Mesh, AM Dot	0.462986	7
12	Uncoated Paper, 100 lpi Mesh, FM Dot	0.333333	10

Table 15

The Grey Relational Grade and Ranking for 70% Print Contrast

Rank	Experimental variables	Grey Relational Grade	Experiment No.
1	Coated Paper, 140 lpi Mesh, AM Dot	1	3
2	Coated Paper, 120 lpi Mesh, AM Dot	0.861357	2
3	Coated Paper, 140 lpi Mesh, FM Dot	0.805676	6
4	Uncoated Paper, 140 lpi Mesh, AM Dot	0.612611	9
5	Coated Paper, 120 lpi Mesh, FM Dot	0.555078	5
6	Uncoated Paper, 140 lpi Mesh, FM Dot	0.554395	12
7	Coated Paper, 100 lpi Mesh, AM Dot	0.439206	1
8	Coated Paper, 100 lpi Mesh, FM Dot	0.41748	4
9	Uncoated Paper, 120 lpi Mesh, AM Dot	0.407046	8
10	Uncoated Paper, 120 lpi Mesh, FM Dot	0.369722	11
11	Uncoated Paper, 100 lpi Mesh, AM Dot	0.344066	7
12	Uncoated Paper, 100 lpi Mesh, FM Dot	0.333333	10

Table 16 (part 1)

The Grey Relational Grade and Ranking for Overall Performance

Experiment No.	Experimental variables	Grey Relational Grade	Rank
3	Coated Paper, 140 lpi Mesh, AM Dot	0.946872	1
2	Coated Paper, 120 lpi Mesh, AM Dot	0.806994	2
6	Coated Paper, 140 lpi Mesh, FM Dot	0.762878	3
5	Coated Paper, 120 lpi Mesh, FM Dot	0.66214	4
12	Uncoated Paper, 140 lpi Mesh, FM Dot	0.585491	5

Table 16 (part 2)

The Grey Relational Grade and Ranking for Overall Performance

Experiment No.	Experimental variables	Grey Relational Grade	Rank
9	Uncoated Paper, 140 lpi Mesh, AM Dot	0.580119	6
4	Coated Paper, 100 lpi Mesh, FM Dot	0.573608	7
1	Coated Paper, 100 lpi Mesh, AM Dot	0.510501	8
8	Uncoated Paper, 120 lpi Mesh, AM Dot	0.471777	9
11	Uncoated Paper, 120 lpi Mesh, FM Dot	0.460219	10
7	Uncoated Paper, 100 lpi Mesh, AM Dot	0.416251	11
10	Uncoated Paper, 100 lpi Mesh, FM Dot	0.384875	12

The Table 7 shows the GRA index ranking for 30% dot gain, and it is noticed that the print quality of screen printing is highly dependable to the mesh count. Higher the screen mesh count, better will be the reproduction of finer details. The higher screen mesh count facilitates the better carrying of fine dot details of stencil over the mesh and also controls the ink flow through the mesh opening during printing.

At higher mesh count such as 140 lpi and 120 lpi, both coated paper and uncoated paper grades can reproduce the 30% tonal area better than that of 100 lpi mesh count. The 100 lpi screen mesh comparatively contains larger mesh opening and so fails to accurately carry the finer details of stencil on the mesh as well as to control the ink flow through the mesh during printing. The AM dots on coated paper with 140 lpi mesh count gives the best result. Even though, the FM dots at higher screen mesh count also works better at 30% dot area.

The GRA index ranking for 50% Dot gain shown are in Table 8 which indicates that the higher screen mesh count can control the dot gain at those middle tones than that of lower mesh count. Also, with higher screen mesh count the AM dots will perform better than FM dots especially in these middle tone areas. FM dots shows undesirable random shift of tonal values at this middle tone than AM dots. Also, the surface irregularities and porosity of uncoated paper always provides a tendency to undesirably absorb the ink and that will increase the chance of dot gain.

The GRA ranking of 70% Dot Gain as shown in Table 9 indicates that the higher mesh count of screen printing can reproduce better shadow details effectively. The AM dots printed on coated paper with 140 lpi mesh count gives the best result. Higher the screen mesh count better will be the ink flow through the mesh in printing and also better the halftone dot details on stencil over the mesh.

The Tables 10-12 are showing the GRA ranking of Hue Error at 30%, 50% and 70% tonal areas respectively. Higher the mesh count, lower will be the hue error irrespective of percentage dot area. It is observed that hue error is minimum in the case of AM dots in highlight, midtone and shadows. However, the hue error depends on the printing conditions, purity of ink, spectral behaviour of the substrate etc.

The Tables 13-15 shows the GRA index ranking for print contrast at 30%, 50% and 70% tonal areas respectively. All the cases indicate that, higher the mesh count better will be the print contrast. Lowering the mesh count will reduce the print contrast of reproduction.

The AM dot print with 140 lpi screen mesh count on coated grade paper shows the superior print contrast in all the cases. At higher screen mesh count the coated paper provides greater print contrast than uncoated grade. The print contrast indicates the accuracy of tonal area reproduction or shadow details in contrast with the solid area ink density.

The overall GRA index-based ranking given in Table 16 indicates that, at 140 lpi screen mesh count, the coated paper with AM dots is comparatively best in the print quality by considering the criteria like solid ink densities, dot gain, hue error and the print contrast. The result shows the importance of mesh count in screen printing in distinction with the type of substrate and the halftone mode of reproduction employed in the printing process.

As per the results, the screen mesh with higher thread counts such as 140 lpi is capable to deliver better print quality in screen printing than that of screen mesh with 120 lpi and 100 lpi mesh count. The screen mesh with high thread count indicates the less open area and its capability to hold more stencil details over the mesh than that of screen with lower mesh count.

Also, the lesser open area of 140 lpi screen mesh facilitates the better control over the ink flow through the mesh and thereby reduces the chance of dot gain under the circumstance of high squeegee pressure and low viscous screen printing ink.

Also, it is noticed that, the irregular surface textured substrate such as uncoated paper in such cases will accelerates the occurrence of undesirable dot gain at lower mesh count in screen printing.

It is also observed that the mode of halftone screening process such as AM and FM dots employed in the printing process influences the print quality.

Comparing AM with FM print quality in the result, it is found that the AM dot pattern gives the best print results at 30%, 50% and 70% tonal areas than FM dots. This indicates that AM dots in middle-tone areas can produce better details in screen printing.

The FM dots are capable to reproduce vibrant colour than AM dots but shows an undesirable random shift of tonal values from highlight to shadow region. This leads to the loss of details at the middle-tones considerably. At the same time, the AM dots are better in reproducing middle tone gradations when comparing with FM dot reproduction.

The problem faced by FM dots in this kind may be due to its fine size and the randomly distributed feature that all made it less likely capable to the various features of screen printing process like: complications of stencil making process, mesh opening, stencil adhesion requirements with the screen, squeegee pressure, ink pigment particle size and its viscosity etc.

The microscopic view of the dot reproduction is shown vide in Figures 9-14 that gives a better understanding about the nature of dot reproduction of both AM and FM dots on coated and uncoated grade paper at different screen mesh count.

Figures 9a-9f represent the microscopic image (enlarged to 80x) of 30% dot area printed on both coated and uncoated paper substrates produced by different combinations of screen mesh. The image is made up of AM dots only. Figure 9c shows that 140 lpi screen mesh on coated paper provides the sharp image with uniform ink distribution which confirms the Taguchi's GRA ranking made in the analysis. Figure 9b represents image printed through 120 lpi on coated images are darker in appearance and hence it confirms the analysis made by Taguchi's GRA method which is the second best.

Figures 10a-10f show the microscopic images of 50% dot area of print made up of AM dots on both coated and uncoated papers by using stencils made on different screen meshes. Figure 10c shows 140 lpi mesh gives the best print quality as compared to others. This confirms the Taguchi's GRA analysis results as obtained.

Figures 11a-11f represent the microscopic images of 70% dot area of print of grey scale formed with AM dots taken on both coated and uncoated paper substrates through the stencils formed on different screen meshes. Figure 11c shows the minimum dot gain as compared to others. This confirms the Taguchi GRA analysis as given in Table 9 and Table 16.

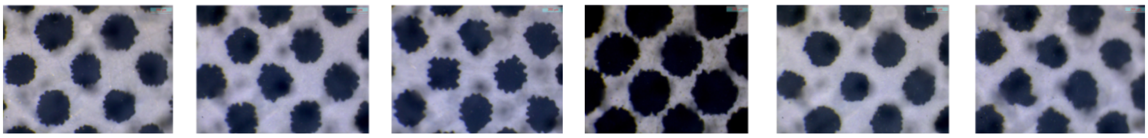
Figures 12a-12f are the microscopic images of the prints of 30% dot area obtained through stencils made on different lpi screen mesh adopting FM dots. The pictures show dot gain is minimum in print of 140 lpi mesh on coated paper but dots are irregular in shape in all the cases.

Figures 13a-13f represent the microscopic images of prints obtained through stencils made on different lpi screen mesh by using FM screening. These shows that dots are not at all clear and gain is more in all the cases.

Figures 14a-14f are the microscopic images of 70% dot area of FM dots through the stencils made on different lpi screen meshes. This shows dot gain is minimum in case of 140 lpi mesh on coated paper vide Figure 12c which confirms the Taguchi's GRA analysis.

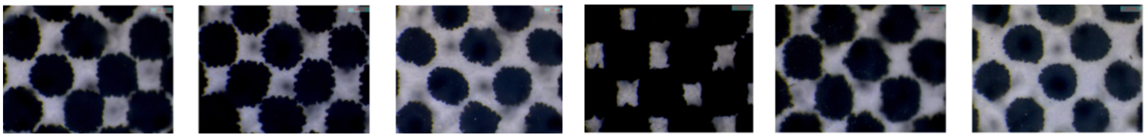
Conclusion

The experimental study conducted with this research work was designed in such a way to find the influence of AM and FM dots on coated and uncoated paper under three different screen mesh ruling in the screen printing process. The print quality assessment was done through the scientific approach of Taguchi's Grey Relational Analysis by considering the major factors influencing the print quality such as solid ink density, dot gain, hue error



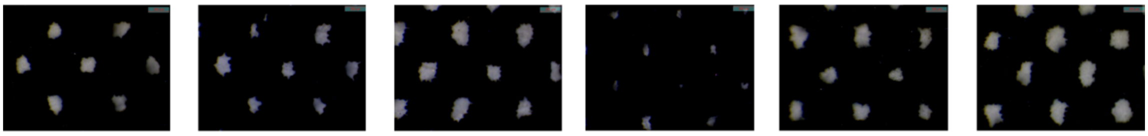
100 lpi, Coated Paper (a) | 120 lpi, Coated Paper (b) | 140 lpi, Coated Paper (c) | 100 lpi, Uncoated Paper (d) | 120 lpi, Uncoated Paper (e) | 140 lpi, Uncoated Paper (f)

» **Figure 9:** *The microscopic view of AM dot at 30% dot area*



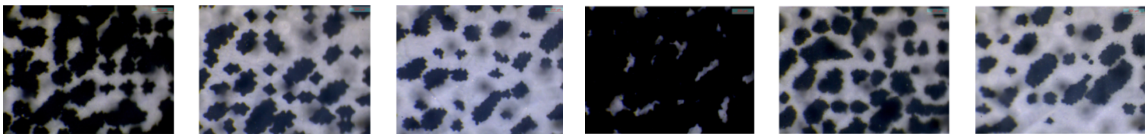
100 lpi, Coated Paper (a) | 120 lpi, Coated Paper (b) | 140 lpi, Coated Paper (c) | 100 lpi, Uncoated Paper (d) | 120 lpi, Uncoated Paper (e) | 140 lpi, Uncoated Paper (f)

» **Figure 10:** *The microscopic view of AM dot at 50% dot area*



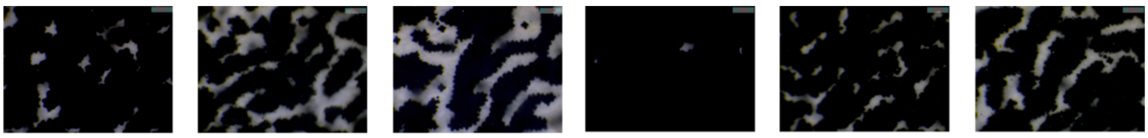
100 lpi, Coated Paper (a) | 120 lpi, Coated Paper (b) | 140 lpi, Coated Paper (c) | 100 lpi, Uncoated Paper (d) | 120 lpi, Uncoated Paper (e) | 140 lpi, Uncoated Paper (f)

» **Figure 11:** *The microscopic view of AM dot at 70% dot area*



100 lpi, Coated Paper (a) | 120 lpi, Coated Paper (b) | 140 lpi, Coated Paper (c) | 100 lpi, Uncoated Paper (d) | 120 lpi, Uncoated Paper (e) | 140 lpi, Uncoated Paper (f)

» **Figure 12:** *The microscopic view of FM dot at 30% dot area*



100 lpi, Coated Paper (a) | 120 lpi, Coated Paper (b) | 140 lpi, Coated Paper (c) | 100 lpi, Uncoated Paper (d) | 120 lpi, Uncoated Paper (e) | 140 lpi, Uncoated Paper (f)

» **Figure 13:** *The microscopic view of FM dot at 50% dot area*

100 lpi, Coated Paper (a) | 120 lpi, Coated Paper (b) | 140 lpi, Coated Paper (c) | 100 lpi, Uncoated Paper (d) | 120 lpi, Uncoated Paper (e) | 140 lpi, Uncoated Paper (f)

» **Figure 14:** *The microscopic view of FM dot at 70% dot area* and print contrast. The tonal reproduction curve at 5% to 100% dot coverage is plotted for dot area, dot gain, hue error and the print contrast. Moreover, this research work employed the systematic implementation of Taguchi's Grey Relational Analysis Technique in the print quality assessment in a most reliable and meaningful way.

The results show that the screen printing quality is dependent on the screen mesh count. Printing with a high screen mesh counton smooth surface paper will give the best result in screen printing. The AM dots will work better in the middle tone region with a good tonal value transition from highlight to shadow region. Meanwhile, the FM dots are capable to give the vibrant color especially at the solid density regions than that of AM dots but fail to reproduce the middle tone densities with a smooth tonal transition. There is a huge shift of tonal value are obtained at the middle tones for FM dots. The accurate reproduction of FM dots in screen printing is dependent on the mesh count and some other crucial factors like adaptation with proper stencil making process, adhesion with screen mesh, squeegee pressure, ink parameters etc. The printing on uncoated paper with low mesh count will leads to high dot gain and it is a poor choice for high quality precision works.

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