Optimization of machining parameters for a light guide plate printing process using Grey relational analysis

Te-Chang Tsai, Ko-Ta Chaing, Fu-Ping Chang, Chih-Chung Chou

Abstract

This paper applies the orthogonal array with the grey relational analysis to optimize the printing machining parameters of light guide plate (LGP) considering the multiple performance characteristics. The application of grey relational analysis can convert the optimization of multiple performance characteristics into the optimization of a single performance characteristic. As a result, this technique can greatly simplify the optimization procedure of the complicated multiple performance characteristics. In this paper, the printing machining parameters, namely mixed rate of ink, velocity and pressure of printing process, and material and angle of scraper are optimized with considerations of multiple performance characteristics including illumination, homogeny, value of variance for the illumination and printing ink thickness. The experimental results using the optimal setting have obviously shown that the above performance characteristics in the printing process can be improved effectively together through this approach.

Keywords：grey relational analysis, illumination, homogeny, performance characteristic, optimization.

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使用灰色關係分析法於導光板印刷過程中加工參數之最佳化

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摘 要

本論文使用正交陣列法結合灰色關係分析法於導光板印刷過程中，在多重品質特性要求下獲得其加工參數之最佳化。應用灰色關係分析法可以將多重品質特性的最佳化問題轉換成單一品質特性的最佳化問題，稱爲灰色關係級數。經由實驗結果所示，此一技巧可以大量簡化其多重品質特性的最佳化問題。在本論文中，有關印刷過程加工參數包含有油墨比例、印刷速度與壓力、刮刀的材質與角度等，而其多重品質特性則有輝度、均齊度、輝度的變異量與印刷厚度等。實驗結果證實在本研究中所獲得最佳化加工參數組合對於所要求的多重品質特性上有著很明顯地一起獲得提升的趨勢。

關鍵詞：灰色關係分析法、輝度、均齊度、品質特性、最佳化。

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1. Introduction

The increasing application of the liquid crystal display (LCD) in the computer, communication and consumer electronic (3C) products, such as notebook personal computers, screens for TV-games, screens for portable television sets, view-finders for video-recorders, etc., is due to the fast developing technology, continuous refined quality and decreasing price. The revelation of LCD depends on the source of backlight, which presents the form of a backlight unit with light guide plate (LGP) being its main component [1-3]. For the large dimensional LCD it extremely needs the higher performance of a backlight unit including high illumination, low cost, low power consumption, and thin thickness. The maximum function of LGP is to uniformly scatter the light and to diminish the variation of light and shade. The material of LGP is propylene (Acryl) and the use of distinct density, different size of diffused point in the bottom of LGP acquires a uniform radiation. The manufactures of LGP have the no-printing type and the printing type. The former type designs the diffused point on the mold to form during the injection molding process immediately. The latter type uses the method of halftone to print the high reflective and no-absorb light printing ink in the bottom of plate forming the diffused point. However the benefits of the printing manufacture type of LGP have the lower developing cost and speedy procreation so that this manufacture type is presently becoming the principal method. The demands of optical characteristic of LGP include both the illumination and the homogeny because the above characteristics will immediately influence the display quality of LCD. The printing ink thickness effects the light refraction and also involves the capitalized cost. Therefore, for the printing process of LGP, it is a critical important to effectively acquire the optimal machining parameters and adjusting factors for decreasing trail-and-error time and consuming cost in which the multiple performance characteristics of brightness, homogeny and printing ink thickness are requested in the meantime.

In order to find an optimal machining condition of the LGP printing process, a large number of experiments are required to prepare test specimens and also to carry out great quantity measurement. The effective experimental design is desirously required to reduce the amount of experiments. Among several experimental design techniques, the grey relational analysis theory has been successfully applied for a systematic approach to optimize designs and to achieve manufacturing parameters. Lin et al. [4] and Singh et al. [5] had used this methodology for optimizing the process parameters of electrical discharge machining of SKD11 and Al-10%SiCp alloy steel, respectively, considering the multiple performance characteristics. The grey relational analysis theory makes use of grey relational generating and calculates the grey relational coefficient to handle the uncertain systematic problem under the status of only partial known information [6,7]. The grey relational coefficient can express the relationship between the desired and actual experimental results and the grey relational grade is simultaneously computed corresponding to each performance characteristic. The single grey relational grade can provide an optimal constitute of process parameters in which the manufacture simultaneously requests of multiple performance characteristics [8, 9]. The optimal levels of process parameters are confirmed through the level with the highest grey relational grade.

The main objective of the present study is to apply the orthogonal array with the grey relational analysis for establishing the optimal set of maching parameters with considerations of multiple performance characteristics in the LGP printing process. Through the grey relational analysis, it is shown by this study that the optimization of complicated multiple performance characteristics can be converted into the optimization of a single grey relational grade.

2.Printing manufacture of light guide plate

The productive principle of the printing type LGP is to spread the high reflective and no-absorb light printing ink (SiO_2 and TiO_2) on its bottom which reflects and extends the light causing the uniformly distributive illuminant in the bright area. The LGP manufacturing process includes the design of diffused point, the manufacture of diffused point's halftone, the printing process and quality restriction. The key factor in the demands of optical characteristic in the manufacturing process is the printing process. The mixture of printing ink and related machining parameters containing the material and angle of scraper, the velocity and pressure of printing process, greatly affect optical characteristic during the printing process. The flow chart of printing procedure is illustrated in Fig. 1. The mixed process of printing ink deals properly with the high reflective and no-absorb light printing ink inducing the function of reflection and diffusivity for a light source. These functions are used to reflective and diffusive the light on the bright area from a light source near the side of LGP. Especially, if the function of diffusivity is inadequate then it will result the non-uniformly distributive illuminant on the different position of the bright area. The setting machining parameters of scraper in the printing process also significantly influence the illumination and homogeny of light in the bright area. The quality restriction of LGP is requested to achieve the demands of customer, such as higher the illumination and homogeny on the bright area and an appropriate amount of printing ink thickness. Therefore, the variations in printing machining parameters such as the mixed rate of ink, the material and angle of scraper, and the velocity and pressure of printing process, affect the performance characteristics of LGP including the illumination, the homogeny and the printing ink thickness. The optimal selection of the machining parameters can result in better performance characteristics of LGP in the printing procedure.

2.1 Selection of machining parameter

The experimental studies were performed on the ATMART56/G high precision opto-electronics screen printer in the white room. The velocity of printing head and the pressure of gas source were set in the range of 0-835 mm/s and 5-8 kg/cm^2, respectively. The six inch type of LGP was used as the experimental object and the light emitting diode was used as a light source in this study. In the standard demands of optical characteristic for a commercial LGP, the criterion of illumination is over 330 cd/m, the percentage of homogeny is over 70% and the printing ink thickness is set as $8 \pm 1\,\mu$m, respectively. The factors of machining parameters and the factor levels were identified according to the characteristics of PGL and the correlated processing parameters of mechanical equipment. As shown in Table 1, this study specifies five principal machining parameters including the mixed rate of ink, the velocity and pressure of printing process, and the material and angle of scraper. To perform the experimental design, the above each machining parameter was designed to have four levels, denoted 1, 2, 3 and 4. The mixed rate of ink was selected according to the criterion of brightness and homogeny in the range of 30-45%. The velocity and pressure during printing process were adjusted form 400 mm/s to 550 mm/s and 5.5 kg/cm^2 to 7.5 kg/cm^2, respectively. The material and angle of scraper were set in the range of HRC 60-75 and 70-85^{O}, respectively. The interaction between the machining parameters is neglected in this study. The initial machining parameters for the printing procedure of LGP were ink's mixed rate of 30%, printing velocity of 450 mm/s, printing pressure of 6 kg/cm^2, scraper material of HRC 65 and scraper angle of 75^{O}.

2.2 Evaluation of performance characteristics

In this study, the illumination, the homogeny and printing ink thickness were used to evaluate the performance characteristics. The illumination is measured by using the equipment of Spectrascan Colorimeter. The value of illumination given in the study is the mathematical average of thirteen measurements as shown in Fig. 2, denoted $\overline{Y}$ (unit cd/m^2). The ratio of maximum value to minimum value of measured illumination is used to express the homogeny on the bright area. The homogeny is calculated by using the following formula:

$$\text{homogeny} = \frac{Y_{\min}}{Y_{\max}} \times 100\% \qquad (1)$$

where $Y_{\min}$ and $Y_{\max}$ are the minimum and maximum value of measured illumination on the bright area, respectively. The higher value of homogeny indicates that the variation of illumination is small and the bright area will be uniform brilliant. Furthermore, The value of variance for the illumination of all measured point is used to confirm the situation of brightness using the frame of statistics. The value of variance (VAR) can be expressed as

$$\text{VAR} = \sqrt{\frac{\sum (Y_i - \overline{Y})^2}{N-1}} \qquad (2)$$

where Y_i is the value of illumination for the *i*th measured point and *N* are the number of measured point on the bright area, respectively. The thickness of printing ink thickness is measured by using the profilemeter (3D- Hommelewerk). The measured point is posited in the center of bright area and the measured unit is μm.

Basically, the higher illumination and homogeny in the printing process are the better performance characteristics. However, the smaller value of variance for the illumination of all measured point is also the better performance characteristic. Therefore, the former both performance characteristics are regarded as larger-the-better characteristics and the latter performance characteristic is the smaller-the-better characteristic and they influence each other relatively. The printing ink thickness is set in the target of commercial demands and regarded as nominal-the-better characteristic.

3. Determination of optimal machining parameters

3.1 Orthogonal array table

The settings of machining parameters for the printing procedure of LGP are determined by using the Taguchi experimental design method. The benefit of Taguchi method [10-13] with the robust design is to simplify a great quantity of fully factor experimentation based on the design of experiments (DOE). This study adopts the factional factorial experimental design which called an orthogonal array and become more effective method to practicing engineers and scientists.

According to the $L_{16}(4^5)$ orthogonal arrays table of the Taguchi method, it selects and disposes the parameter condition of five processing factors and four levels for performing the experimental design, as shown in Table 2. The numbers in each column express the levels for the specific factors. In the L_{16} orthogonal arrays table, sixteen experiments are used to investigate the total performance characteristics. In order to obtain a more accurate result, each experiment was repeated three times in this process. The test association of every processing factor, provided from the orthogonal arrays table, obtains the results of four performance characteristics including the illumination, the homogeny, the value of variance of the illumination, and the printing ink thickness, respectively, and is listed in Table 3.

3.2 Grey relational analysis for the experimental results

The grey means the primitive data with poor, incomplete and uncertain information in the grey systematic theory, the incomplete relation of information among this data is called the gray relation. Grey relational analysis is to compare quantitative analysis to the development between every factor in the grey system dynamically, describes the relation degree between main factor and other factors in the grey system. In the grey relational space, the set of sequence X_i is expressed as

$$X_i = [X_i(1), X_i(2), \cdots, X_i(k)],\quad i \in I, k \in N \tag{3}$$

where $X_i(k), i \neq 0$ is the compared sequence and $X_0(k)$ is the reference sequence. The grey relational coefficient for $X_i(k)$ to $X_0(k)$ is calculated as [4-7]

$$r_i(k) = r[X_0(k), X_i(k)] = \frac{\Delta\min + \xi\Delta\max}{\Delta_{o,i}(k) + \xi\Delta\max} \tag{4}$$

where $\Delta_{0,i}(k) = \left|X_0(k) - X_i(k)\right|$ is the absolute value of differences of $X_i(k), i \neq 0$ and $X_0(k)$, ξ is the distinguish coefficient which its value is adjusted with the systematic actual need and defined in the range between 0 and 1 [4-7]. The $\Delta\min = \min\limits_{i\in I}\min\limits_{k}\left|X_0(k) - X_i(k)\right|$ and $\Delta\max = \max\limits_{i\in I}\max\limits_{k}\left|X_0(k) - X_i(k)\right|$ are defined as the minimum and maximum value of $\Delta_{0,i}(k) = \left|X_0(k) - X_i(k)\right|$, respectively. Then the grey relational grade for X_i to X_0 is expressed as

$$r(X_0, X_i) = \frac{1}{n}\sum_{k=1}^{n} r[X_0(k), X_i(k)] = \frac{1}{n}\sum_{k=1}^{n} r_i(k) \tag{5}$$

From the above discussion, the use of the quantity model of grey relational analysis establishes the analytic processing step that includes the following steps:

(1) normalizing the experimental results of multiple performance characteristics,

(2) performing the value of $\Delta_{0,i}$, $\Delta\min$ and $\Delta\max$ to calculate the grey relational coefficient $r_i(k)$,

(3) calculating the grey relational grade r by the mean value of grey relational coefficient $r_i(k)$,

(4) performing the response table and response graph for each level of the machining parameters,

(5) recognizing the noticeable and unnoticeable variable factors by statistical analysis of variance (ANOVA),

(6) selecting the optimal levels of machining parameters,

(7) confirms tests and verify the optimal machining parameters setting.

In this grey relational analysis, the single grey relational grade can easy simplify the optimization of process parameters in which the manufacture simultaneously requests of complex multiple performance characteristics. The level of machining parameter with the highest grey relational grade has been set for the optimal level.

3.3 Normalizinge the experimental results of each performance characteristic

The linear normalization of the experimental results for the illumination, the homogeny, the value of variance of the illumination, and the printing ink thickness were performed in the range between 0 and 1, which is called the grey relational generating. The performance characteristics of printing process include the larger-the-better, smaller-the-better and nominal-the-better characteristics. Consequently the normalized experimental results can be expressed as:

for larger-the-better characteristic

$$X_i^*(k) = \frac{X_i(k) - \min\limits_{\forall k} X_i(k)}{\max\limits_{\forall k} X_i(k) - \min\limits_{\forall k} X_i(k)} \quad (6)$$

and for smaller-the-better characteristic

$$X_i^*(k) = \frac{\max\limits_{\forall k} X_i(k) - X_i(k)}{\max\limits_{\forall k} X_i(k) - \min\limits_{\forall k} X_i(k)} \quad (7)$$

and for nominal-the-better characteristic

$$X_i^*(k) = 1 - \frac{|X_i(k) - X_{ob}(k)|}{\max\limits_{\forall k} X_i(k) - \min\limits_{\forall k} X_i(k)} \quad (8)$$

where $X_i(k)$ is kth experimental results in the ith experiment, $\max\limits_{\forall k} X_i(k)$ and $\min\limits_{\forall k} X_i(k)$ is the largest and smallest value of $X_i(k)$ for kth experimental results, respectively, and $X_{ob}(k)$ is the target of kth experimental results.

In the grey relational analysis the normalized results reveal the situation of better performance. The large value of normalized results can express the better performance and the best-normalized results will be equal to one. Table 4 shows the normalized results for the illumination, the homogeny, the value of variance of the illumination, and the printing ink thickness after the grey relational generating.

3.4 Calculate the grey relational coefficient and grade

The grey relational coefficient is calculated to display the relationship between the optimal (best = 1) and actual normalized results. According to the data of Table 4, the use of $\Delta_{0,i}$, $\Delta\min$ and $\Delta\max$ calculate the grey relational coefficient $r_i(k)$ for each experiment respectively. The higher grey relational coefficient $r_i(k)$ represents that the corresponding experimental result is closer to the optimal (best) normalized value for the single performance characteristic.

The experimental No.10, 16, 3 and 10 in

the Table 4 have the best performance characteristic for the illumination, the homogeny, the value of variance of the illumination, and the printing ink thickness, respectively. The result of grey relational grade r for the multiple (total) performance characteristics are tabulated in Table 5. The single grey relational grade r can handle the optimization of the complicated multiple performance characteristics. From the grey relational grade r, the relational degree between main factor and other factors is computed concerning of each performance characteristic. Hence the higher grey relational grade r indicates that this experimental result is approach to the ideally normalized value. In this study, the experimental No. 10 has the best the multiple (total) performance characteristics among total experiments in Table 5.

3.5 Analyze the results of grey relational grade

The response table and response graph of factors with the mean grey relational grades are shown in Table 6 and Fig. 2, respectively. The response table and response graph are obtained from the average value of the grey relational grade for each level of the machining parameters in order to select the composition of optimal factors. The optimal setting of machining parameter selects the level with higher value of grey relational grade for each operating factor concerning the illumination, the homogeny, the value of variance of the illumination, and the printing ink thickness. The value of grey relational grade for each operating factor concerning multiple performance characteristics is the greater the better in the response table. From Table 6, the level constitutions of optimal machining parameters are A3, B2, C3, D3 and E1 for maximizing the illumination and the homogeny, for minimizing the value of variance of the illumination, and for easy setting the demandable thickness of printing ink simultaneously.

The steep slope of response graph indicates the more influence of operating factor to the performance characteristic in the Fig. 3. Results show that the first three operating factors namely (A) the mixed rate of ink, (C) the printing pressure and (B) the printing velocity have greater value of steep slope and more influences on the multiple performance characteristics.

The contributions of machining parameters on the multiple performance characteristics are obtained by the decomposition of variance, which is called analysis of variance (ANOVA). In general, the terms in ANOVA are typical depicted as the flowing [14].

$$SS_{total} = \sum_{i=1}^{n} \sum_{j=1}^{l} r_{ij}^2 - n\,l\,r_m^2 \qquad (9)$$

$$SS_{factor} = \frac{nl}{L} \sum_{k=1}^{L} (r_k - r_m)^2 \qquad (10)$$

$$DOF_{total} = n \times l - 1 \qquad (11)$$

$$DOF_{factor} = L - 1 \qquad (12)$$

$$V_{factor} = \frac{SS_{factor}}{DOF} \qquad (13)$$

$$F_{factor} = \frac{V_{factor}}{V_{error}} \qquad (14)$$

where SS_{total} is the total sum of squares, SS_{factor} is the factorial sum of squares, n is the number of experiments, l is the number of specimens taken, DOF is the number of degrees of freedom, L is the number of factor's level, V_{factor} is the variance of the factor, F_{factor} is the F ratio of the factor and r_m is the total mean of the grey relational grade. Statistically, the Fisher's F test [14] provides a decision at some confidence level as to whether these parameters are significantly effect on the performance characteristic. Large F-value indicates that the change of the machining parameter makes a significant effect on the performance characteristic. From the results of analysis of variance in the Table 7, the percent contribution of first three significant machining parameters namely (A) the mixed rate of ink, (C) the printing pressure and (b) the printing velocity are 27.87%, 25.54% and 24.00%, respectively. From the F-test analysis those parameters have been regarded as the significant factor again. From the results of contribution, the above three factors are noticeable variable factors as the resources of increasing quality. The other operating factors are regarded as unnoticeable variable factors to reduce production costs.

3.6 Verification tests

Since the optimal levels of machining parameters have selected, the confirmation tests are processed to verify the improvement of total performance characteristics. The result of the confirmation experiment is expressed by the estimated grey relational grade $\hat{r}$. The estimated grey relational grade $\hat{r}$ for the optimal levels of machining parameters can be calculated as:

$$\hat{r} = r_m + \sum_{i=1}^{\alpha} (\bar{r}_i - r_m) \qquad (15)$$

where r_m is the total mean of the grey relational grade, $\bar{r}_i$ is the mean of the grey relational grade at the optimal level and α is the number of machining parameters. The estimated grey relational grade $\hat{r}$ using the optimal machining parameters can be found out even for the setting not available in the orthogonal arrays table. Table 8 shows the comparison of multiple performance characteristics with the initial and optimal machining parameters. The initial design machining parameters are A1, B2, C2, D2 and E2, which is the experiment 2 in the Table 5. As shown in Table 8, the results of optimal machining parameters indicate that the illumination is improved from 328.387 to 342.452 cd/m^2, the homogeny is increased from 62.62 to 72.15%, the value of variance of the illumination is reduced from 2.507 to 2.135 and thickness of printing ink is easy setting 8.01 μ m. The estimated grey relational grade $\hat{r}$ has increased and is larger than all the grey relational grades r in the Table 5. Consequently, it is shown clearly the total performance characteristics in the LPG printing process are greatly improved through this study.

4. Conclusion

The use of the orthogonal array with the grey relational analysis to determine the optimal machining parameters of LGP printing process with consideration of multiple performance characteristics has been investigated in this study. The application of grey relational analysis can convert the optimization of multiple performance characteristics into the optimization of a single performance characteristic. From the experimental results, this technique can greatly simplify the optimization procedure of the complicated multiple performance characteristics. Results represent that the multiple performance characteristics of the printing process including the illumination, the homogeny, the value of variance of the illumination, and the printing ink thickness are greatly improved together by using this method proposed by this study.

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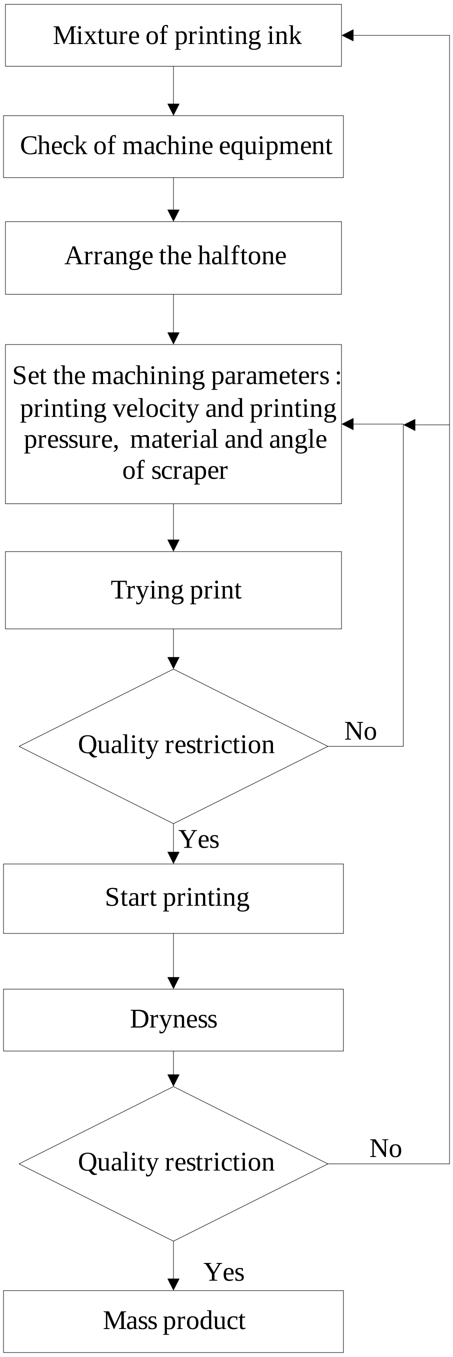

Fig. 1. The printing procedure of LGP.

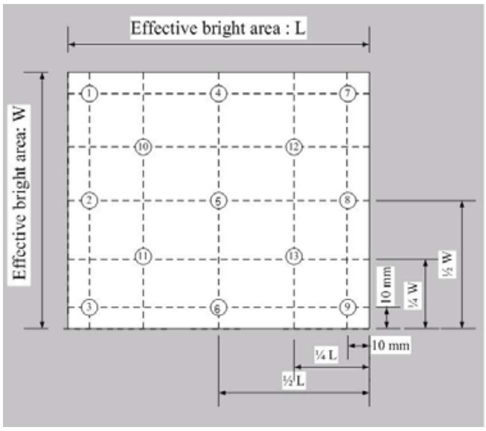

Fig. 2. The positions of measured point for the value of illumination.

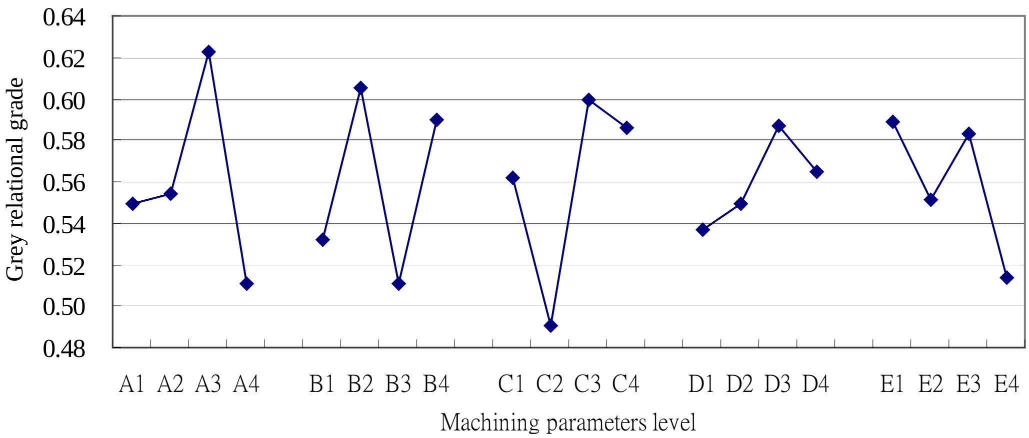

Fig. 3. The response graph for each level of the machining parameters.

Table 1. Factors and levels.

Symbol	Factors	unit	Level			
			1	2	3	4
A	mixed rate of ink	%	30	35	40	45
B	velocity	mm/s	400	450	500	550
C	pressure	kg/cm^2	5.5	6	6.5	7
D	material of scraper	HRC	60	65	70	75
E	angle of scraper	degree	70	75	80	85

Table 2. Experimental layout using an L_{16} orthogonal array

No.	Machining parameter				
	A	B	C	D	E
	mixed rate of ink	velocity	pressure	material of scraper	angle of scraper
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

Table 3. Experimental results for the illumination, the homogeny, the value of variance of the illumination, and the printing ink thickness.

No.	illumination(cd/m^2)			Homogeny(%)			value of variance of the illumination			printing ink thickness(μm)		
	1	2	3	1	2	3	1	2	3	1	2	3
1	325.67	326.03	326.34	64.18	64.34	65.11	2.494	2.497	2.592	7.87	7.89	7.85
2	328.87	327.56	328.73	62.31	62.35	63.21	2.512	2.503	2.507	8.21	8.24	8.18
3	326.56	325.32	325.78	61.19	61.48	62.11	2.432	2.453	2.433	8.25	8.27	8.22
4	332.97	334.23	333.12	66.03	66.56	66.98	2.469	2.475	2.472	8.47	8.51	8.49
5	332.86	333.67	333.45	62.65	62.73	63.22	2.592	2.601	2.560	8.50	8.53	8.47
6	333.24	332.56	333.54	68.54	68.94	69.03	2.563	2.583	2.576	7.98	8.01	7.87
7	335.54	334.23	335.23	65.32	65.43	66.22	2.573	2.568	2.578	8.38	8.41	8.35
8	336.24	337.23	337.21	64.72	65.01	65.21	2.434	2.446	2.442	8.48	8.51	8.47
9	335.45	336.11	335.67	69.15	70.01	70.12	2.487	2.492	2.489	8.51	8.53	8.43
10	341.45	342.11	342.45	68.13	68.79	69.21	2.496	2.501	2.495	7.78	7.84	7.73
11	333.54	333.67	334.05	65.86	66.32	66.43	2.523	2.532	2.528	8.34	8.51	8.33
12	336.45	336.78	337.01	68.84	69.03	69.21	2.564	2.571	2.568	8.30	8.43	8.35
13	330.25	331.23	331.76	62.24	62.87	62.98	2.543	2.552	2.547	8.08	8.14	8.11
14	329.56	330.01	330.56	70.35	70.83	70.53	2.562	2.568	2.572	7.07	7.15	7.11
15	328.67	327.32	328.32	58.76	59.03	59.12	2.576	2.581	2.574	8.27	8.35	8.21
16	330.67	331.54	331.23	70.21	70.77	70.98	2.523	2.534	2.528	8.80	8.91	8.74

Table 4. The normalized experimental results

No.	illumination			Homogeny			value of variance of the illumination			printing ink thickness		
	1	2	3	1	2	3	1	2	3	1	2	3
Ideal	1	1	1	1	1	1	1	1	1	1	1	1
1	0.000	0.042	0.034	0.613	0.671	0.000	0.468	0.450	0.505	0.925	0.938	0.908
2	0.203	0.133	0.177	0.500	0.632	0.535	0.306	0.281	0.345	0.879	0.864	0.890
3	0.056	0.000	0.000	1.000	0.955	1.000	0.210	0.208	0.252	0.855	0.847	0.865
4	0.463	0.531	0.440	0.769	0.813	0.755	0.627	0.638	0.663	0.728	0.710	0.699
5	0.456	0.497	0.460	0.000	0.000	0.204	0.336	0.314	0.346	0.711	0.699	0.712
6	0.480	0.431	0.466	0.181	0.116	0.101	0.844	0.840	0.836	0.988	0.994	0.920
7	0.625	0.531	0.567	0.119	0.213	0.088	0.566	0.542	0.599	0.780	0.767	0.785
8	0.670	0.709	0.686	0.987	1.000	0.943	0.514	0.507	0.513	0.723	0.710	0.712
9	0.620	0.643	0.593	0.656	0.703	0.648	0.896	0.931	0.927	0.705	0.699	0.736
10	1.000	1.000	1.000	0.600	0.645	0.610	0.808	0.827	0.851	0.873	0.909	0.834
11	0.499	0.497	0.496	0.431	0.445	0.403	0.613	0.618	0.616	0.803	0.710	0.798
12	0.683	0.683	0.674	0.175	0.194	0.151	0.870	0.847	0.851	0.827	0.756	0.785
13	0.290	0.352	0.359	0.306	0.316	0.283	0.300	0.325	0.325	0.954	0.920	0.933
14	0.247	0.279	0.287	0.187	0.213	0.126	1.000	1.000	0.962	0.462	0.517	0.454
15	0.190	0.119	0.152	0.100	0.129	0.113	0.000	0.000	0.000	0.844	0.801	0.871
16	0.317	0.370	0.327	0.431	0.432	0.403	0.988	0.995	1.000	0.538	0.483	0.546

Table 5. The data of $r_i(k)$ and r

No.	$r_1(k)$	$r_2(k)$	$r_3(k)$	$r_4(k)$	r	Orders
1	0.339	0.488	0.500	0.798	0.531	9
2	0.376	0.421	0.531	0.705	0.508	13
3	0.338	0.392	0.972	0.668	0.592	5
4	0.490	0.583	0.694	0.498	0.566	7
5	0.486	0.428	0.351	0.493	0.439	15
6	0.480	0.757	0.366	0.923	0.632	4
7	0.541	0.537	0.368	0.563	0.502	14
8	0.616	0.506	0.958	0.499	0.645	2
9	0.568	0.860	0.602	0.498	0.632	3
10	1.000	0.745	0.567	0.699	0.753	1
11	0.499	0.565	0.466	0.558	0.522	12
12	0.610	0.777	0.377	0.578	0.585	6
13	0.429	0.423	0.417	0.827	0.524	11
14	0.407	0.976	0.378	0.351	0.528	10
15	0.372	0.333	0.361	0.645	0.428	16
16	0.430	0.989	0.464	0.372	0.564	8

Table 6. Response table for the grey relational grade

Symbol	Machining parameter	Grey relational grade				
		Level 1	Level 2	Level 3	Level 4	Max-Min
A	mixed rate of ink	0.5496	0.5546	0.6231	0.5108	0.1123
B	velocity	0.5317	0.6052	0.5111	0.5900	0.0942
C	pressure	0.5622	0.4901	0.5993	0.5864	0.1092
D	material of scraper	0.5367	0.5498	0.5871	0.5644	0.0504
E	angle of scraper	0.5892	0.5516	0.5834	0.5139	0.0752
Total mean value of the grey relational grade=0.5595						

Table 7. Results of the analysis of variance

Symbol	Machining parameter	DOF	SS	V	F	Contribution
A	mixed rate of ink	3	0.078425	0.026142	88.44251	25.54%
B	velocity	3	0.073692	0.024564	83.10481	24.00%
C	pressure	3	0.085564	0.028521	96.49374	27.87%
D	material of scraper	3	0.016804	0.005601	18.94995	5.47%
E	angle of scraper	3	0.043088	0.014363	48.59153	14.03%
	Error	32	0.009459	0.000296		3.08%
	Total	47	0.307031			100.00%

Table 8. The comparing results of the initial and optimal machining parameters

Machining parameter	Initial	Optimal	
		Prediction	Experiment
Level	A1 B2 C2 D2 E2	A1 B2 C3 D3 E1	A1 B2 C3 D3 E1
illumination(cd/cm)	328.387	342.452	341.563
Homogeny(%)	62.62	72.15	71.65
value of variance of the illumination	2.507	2.135	2.207
printing ink thickness(μm)	8.21	8.01	8.02
Grey relational grade	0.5083	0.7659	0.7614
Improvement of the grey relational grade		0.2576	0.2531