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Multi-objective optimization with modified Taguchi approach to specify optimal robot spray painting process parameters

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Abstract

Robot spray painting process can improve the quality, productivity and provide clean environment in addition to minimize the labour and cost. This process is being used in automobiles, home appliances, etc. There is a need to specify optimal spray painting process parameters to improve the quality of paint coating considering the performance indicators as thickness variation, surface roughness and film adhesion. Compared to the Taguchi orthogonal array and gray rational analysis, a simple modified Taguchi approach is adopted here to identify optimal spray painting process parameters (such as distance, pressure and speed) and obtain minimum thickness variation, minimum surface roughness and maximum film adhesion. Empirical relation for thickness variation, surface roughness and film adhesion are presented. Test data are close-to/within the estimated range.

Keywords: ANOVA; Automated paint; Distance; Film adhesion; Pressure; Speed; Surface roughness; Thickness variation.

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1. Introduction

Spray painting process has been used extensively in automobiles, home appliances etc. In this process, liquid paint is atomized and deposited on the intended surface [19]. The quality of the process is governed by the spray coverage and coating layer thickness.

Robots can automate this spray painting process to improve quality, productivity and clean environment in addition to minimize the cost and labour [38, 36]. It is noted that the paint quality is influenced by transfer rate, pressure, gun travel speed, viscosity, surface preparation, paint composition and temperature. Chemical and environmental properties are in general constant, whereas the pressure, distance between gun and surface, and gun travel speed are influencing the performance indicators [43, 6].

From and Gravdahl [11] have proposed a technique for increasing the speed at which a standard industrial manipulator can paint a wall surface. Abdellatif [1] has described the design and working of an automatic wall painting robot machine. Thakar and Vora [39] have provided information on the manufacture of components and paints requirement for protection from rusting in small scale and medium scale industries. Keerthanaa et al. [15] have followed a procedure using infrared transmitter and flaming receiver for identifying the appearance of the wall; microcontroller unit for regulating the DC motor movement; and the robot to paint the wall surface automatically. Bhalamurugan and Prabhu [3] have examined the performance characteristics of an industrial robot ABB-IRB1410 to develop an automated painting process. They have used Taguchi orthogonal array (OA) and gray relational analysis (GRA). The multi-objective optimization problem is converted to a single objective and carried out optimization using GRA. They have also compared results with those by manual painting using HVLP gun.

Taguchi approach is a systematic statistical approach. The method considers an orthogonal array and suggests few experiments for obtaining the data of the full factorial design of experiments [26] . Adopting this type of approach minimizes the cost of experimentation and time-consuming trial run experiments. The method has been successfully applied for obtaining optimal solutions to many industrial problems such as drilling induced damages in composites [35, 30], performance of plate heat exchangers [42], stage and satellite separation processes of space launch vehicles [32, 33], and the manufacturing processes [27, 7].

Bhalamurugan and Prabhu [3] have designed an experiment for the robot spray painting process to obtain optimal process parameters using Taguchi's L9 orthogonal array for the three process parameters (such as distance, pressure and speed) with three levels. The performance indicators to seek optimal robot spray painting process parameters are thickness variation, surface roughness and film adhesion. Taguchi method is well suited for optimizing the single performance characteristic. They have performed the gray rational analysis (GRA) for obtaining optimal solution to the multi-objective problem consisting of three performance indicators. Analysis of variance (ANOVA) is performed after applying the signal-to-noise (S/N) transformation to a single value of each test run output responses namely (viz., thickness variation, surface roughness and film adhesion). In fact Taguchi has recommended S/N transformation to accommodate scatter in the several repetitions of each test run data into a single value [26]. Though S/N ratio transformations take into account the scatter in test data and provide a single value of the output response for each test run, the additive law [26] estimates the deterministic output response from the mean values. This paper considers the modified Taguchi approach to estimate the range of the output response to the specified robot spray painting process parameters. The estimates of the output responses are compared with test data [3]. The S/N ratio transformation applied by Bhalamurugan and Prabhu [3] leads to the additional computation. The test results [3] are within the estimated range. This comparative study confirms the validation of the modified Taguchi approach in the robot spray painting process.

2. Analysis

Bhalamurugan and Prabhu [3] have carried out experiments on ABB IRB 1410 robot. The specially designed end-effectors with spray gun is pneumatically controlled. A portable paint booth is fabricated to hold the CRCA steel substrates (of $250 \times 150 \times 1.5mm$) in appropriate position and to control the air pollution from the created fumes. Hi-Solids Poly Urethane (PU) with low volatile organic compounds (VOC) is used for painting. Ford#4 cup is used for measuring the paint viscosity. 50% Overlapping is taken for the path planning of the gun travel. To improve the quality of paint coating, thickness variation (ψ_1) , surface roughness (ψ_2) and film adhesion (ψ_3) are considered as the performance indicators whereas as the distance (A), pressure (B) and speed (C) are the spray painting process parameters (see Figure-1). They have set 3 levels for each of the 3 spray painting process parameters. Table-1 gives the levels of the process parameters (A, B and C) and the performance indicators (ψ_1, ψ_2 and ψ_3) for the assigned parameters as per L_9 orthogonal array. The minimum number of experiments ($N_{Taguchi}$) corresponding to the number of process parameters (n_p) and their assigned levels (n_l) is [26]:

$$N_{Taguchi} = 1 + (\text{Number of process parameters}) \times (\text{Number of Levels} - 1) = 1 + (n_p)(n_l - 1) \qquad (1)$$

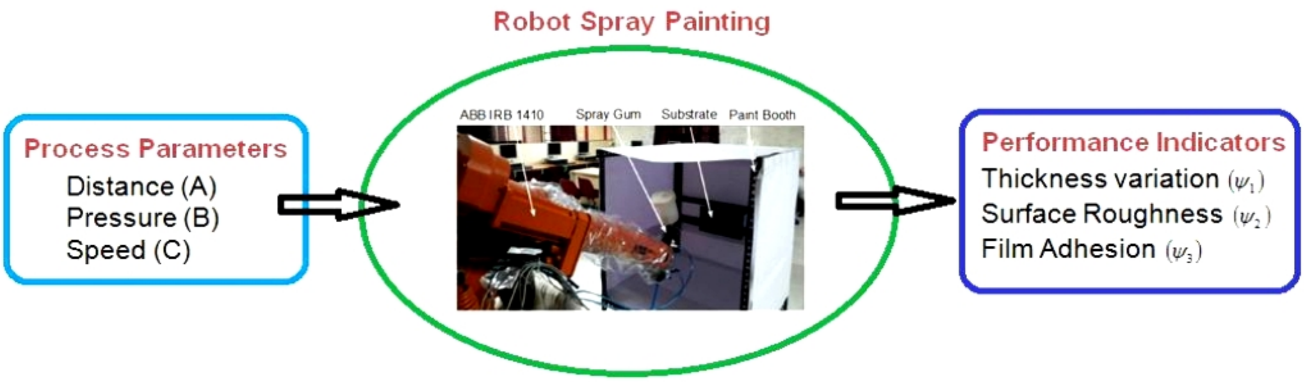

Figure-1: Robot spray painting process parameters and performance indicators [3]

For the present L_9 orthogonal array $N_{Taguchi} = 9$ and $n_l = 3$, equation (1) gives the number of process parameters,$n_p = 4$, which can be accommodated. Ref. [3] considers only three spray painting process parameters. Hence the fictitious factor (D) is introduced in Table 1 as in Ref. [27]. Table-2 presents ANOVA results. Spray painting process parameters viz., distance (A), pressure (B), speed (C) and fictitious parameter (D)have 51.72, 30.17, 13.15 and 4.96% contribution on thickness variation . In case of surface roughness , the spray paint process parameters (A, B, D) and the fictitious parameter (D) have (18.23, 74.31, 6.92 and 0.54) % Contribution. For the case of film $adhesion(\psi_3)$, A, B, C and D have (47.08, 30.2, 19.54 and 3.18) % Contribution. From the ANOVA table the spray painting process parameters for achieving minimum thickness $variation(\psi_1)$ is $A_1B_2C_2$ in which subscriptions denotes the levels of process parameters. For minimum surface $roughness(\psi_2)$, the set of process parameters is $A_3B_2C_1$, whereas for the case of maximum film $adhesion(\psi_3)$, the process parameters are $A_3B_3C_3$. Process designer would like to have a set of spray paint process parameters which assures minimum thickness $variation(\psi_1)$, surface $roughness(\psi_2)$ and maximum film $adhesion(\psi_3)$, Test data from the ANOVA table-2 indicates different optimum process parameters for ψ_1, ψ_2 and ψ_3. In such a situation multi-objective optimization has to be carried out to specify a set of spray paint process parameters for achieving minimum ψ_1 and ψ_2 and maximum ψ_3.

Table-1: Design factors and the performance indicators (viz., thickness $variation(\psi_1)$, surface $roughness(\psi_2)$, and film $adhesion(\psi_3)$) as per L_9 orthogonal array.

Design factors	Designation	Level-1	Level-2	Level-3
Distance (mm)	A	100	125	150
Pressure (bar)	B	2	2.25	2.5
Speed (mm/s)	C	75	90	105
Fictitious	D	d_1	d_2	d_3

Test Run	Levels of design factors				Performance indicators					
					Thickness variation, $\psi_1(\mu m)$		Surface roughness, $\psi_2(\mu m)$		Film adhesion, $\psi_3(\%)$	
	A	B	C	D	Test [10]	Eq.(2)	Test [10]	Eq.(2)	Test [10]	Eq.(2)
1	1	1	1	1	9	9	0.102	0.102	96.5	96.5
2	1	2	2	2	2	2	0.110	0.110	95	95.0
3	1	3	3	3	9	9	0.162	0.162	98.5	98.5
4	2	1	2	3	5.5	5.5	0.104	0.104	97	97.0
5	2	2	3	1	5.5	5.5	0.096	0.096	97.5	97.5
6	2	3	1	2	18	18	0.130	0.130	98.5	98.5
7	3	1	3	2	18	18	0.083	0.083	98.9	98.9
8	3	2	1	3	14	14	0.070	0.070	98.5	98.5
9	3	3	2	1	18	18	0.137	0.137	98.9	98.9

Since ψ_1, ψ_2 and ψ_3 are three different output responses, they must be functionally represented in non-dimensional form. For this purpose the maximum values of ψ_1, ψ_2 and ψ_3 evaluated from the ANOVA table-2 using the additive law (2) are: $\psi_{1max} = 25\ \mu m$, $\psi_{2max} = 0.1653\ \mu m$and $\psi_{3max} = 100.6\%$. Using the additive law, one can estimate the output response $(\widehat{\Psi})$ [26]:

$$\widehat{\Psi} = \Psi_{mean} + \sum_{i=1}^{n_p} (\Psi_i - \Psi_{mean}) \tag{2}$$

Here $\widehat{\Psi}$ is the estimated value of the output response; Ψ_{mean} is the overall mean of the total test runs; Ψ_i is the mean value corresponding to the process parameter at the specified level; and n_p is the number of process parameters. Introducing the fictitious parameter (i.e., $n_p = 4$), the estimates of the output responses using the additive law (2) in Table-1 are closely matching with test results [3].

Table-2: Analysis of variance (ANOVA) for the performance indicators (viz., thickness *variation*(ψ_1) , surface *roughness*(ψ_2) and film *adhesion*(ψ_3))

Design Factors	1-Mean	2-Mean	3-Mean	Mean	Sum of Squares	% Contribution
Thickness variation, $\psi_1(\mu m)$						
A	6.667	9.667	16.667	11	158	51.72
B	10.833	7.167	15	11	92.17	30.17
C	13.667	8.5	10.833	11	40.17	13.15
D	10.833	12.667	9.5	11	15.17	4.96
Surface roughness, $\psi_2(\mu m)$						
A	0.1247	0.1100	0.0967	0.1104	1.177E-03	18.23
B	0.0963	0.0920	0.1430	0.1104	4.798E-03	74.31
C	0.1007	0.1170	0.1137	0.1104	4.469E-04	6.92
D	0.1117	0.1077	0.1120	0.1104	3.489E-05	0.54
Film adhesion, $\psi_3(\%)$						
A	96.67	97.67	98.77	97.7	6.62	47.08
B	97.47	97.00	98.63	97.7	4.25	30.20
C	97.83	96.97	98.30	97.7	2.75	19.54
D	97.63	97.47	98.00	97.7	0.45	3.18

The Taguchi approach is being used for the optimization of single response problems [18]. Tong et al. [40], Anthony [2] and other researchers [12, 10] have considered the multiple quality characteristics simultaneously using the Taguchi quality loss function for multiple responses optimization (viz., the Taguchi based utility concept). A simple and reliable multi-objective optimization approach in [27, 4] similar to the above Taguchi based utility concept is validated by solving different optimization problems [21, 30, 4] which is being followed here. Introducing the positive weighing factors ω_1, ω_2 and ω_3 (which satisfy $\omega_1 + \omega_2 + \omega_3 = 1$), one can write a single function ξ to optimize ψ_1, ψ_2 and ψ_3 in the form

$$\xi = \omega_1\left(\frac{\Psi_1}{\Psi_{1max}}\right) + \omega_2\left(\frac{\Psi_2}{\Psi_{2max}}\right) + \omega_3\left(\frac{\Psi_{3max}}{\Psi_3} - 1\right) \tag{3}$$

Minimization of ξ provides the minimum Ψ_1 and Ψ_2 and maximum $\Psi_3$for the set of spray painting process parameters. To achieve common optimum spray painting process conditions equal weighing factors assigned are: $\omega_1 = \omega_2 = \omega_3 = \frac{1}{3}$. Table-3 gives the generated values of ξ. From equation (3) for each test run ANOVA is performed on ξ in Table-4 for 9 test runs and obtained optimum spray painting process parameters to achieve minimum ξ are: $A_1B_2C_2$ (Distance, $A = 100$ mm; Pressure, $B = 2.25$ bar; and Speed, $C = 90$ mm/s). It is noted from the test run-2 of Table-1 corresponding to the identified optimum spray painting process parameters.

Table-3: Multi-objective function ξ for the performance indicators of Table-1.

Test Run	Levels of design factors				Non-dimensional performance indicators			ζ **(Eq.3)**
	A	B	C	D	$\frac{\psi_1}{\psi_{1\max}}$	$\frac{\psi_2}{\psi_{2\max}}$	$\frac{\psi_{3\max}}{\psi_3}-1$	
1	1	1	1	1	0.36	0.6169	0.0425	0.3398
2	1	2	2	2	0.08	0.6653	0.0589	0.2681
3	1	3	3	3	0.36	0.9798	0.0213	0.4537
4	2	1	2	3	0.22	0.6290	0.0371	0.2954
5	2	2	3	1	0.22	0.5806	0.0318	0.2775
6	2	3	1	2	0.72	0.7863	0.0213	0.5092
7	3	1	3	2	0.72	0.5020	0.0172	0.4131
8	3	2	1	3	0.56	0.4234	0.0213	0.3349
9	3	3	2	1	0.72	0.8286	0.0172	0.5219

Table-4: ANOVA results for the multi-objective optimization function ξ.

Design Factors	1-Mean	2-Mean	3-Mean	Mean	Sum of Squares	% Contribution
A	0.3539	0.3607	0.4233	0.3793	0.0088	11.38
B	0.3494	0.2935	0.4950	0.3793	0.0649	84.05
C	0.3946	0.3618	0.3814	0.3793	0.0016	2.12
D	0.3797	0.3968	0.3613	0.3793	0.0019	2.44

The empirical relations developed for the thickness $variation(\psi_1)$, surface $roughness(\psi_2)$ and film $adhesion(\psi_3)$ in terms of distance (A), pressure (B) and speed (C) are:

$$\Psi_1 = 3.3333 + 5\ \xi_1 + 2\ \xi_1^2 + 2.08333\ \xi_2 + 5.75\ \xi_2^2 - 1.4167\ \xi_3 + 3.75\ \xi_3^2 \quad (4)$$
$$\Psi_2 = 0.0981 - 0.014\ \xi_1 + 0.0007\ \xi_1^2 + 0.02333\ \xi_2 + 0.0277\ \xi_2^2 + 0.0065\ \xi_3 - 3.0098\ \xi_3^2 \quad (5)$$
$$\Psi_3 = 96.2333 + 1.05\ \xi_1 + 0.05\ \xi_1^2 + 0.5833\ \xi_2 + 1.05\ \xi_2^2 + 0.2333\ \xi_3 + 1.1\ \xi_3^2 \quad (6)$$

Here, $\xi_1 = 0.04\ A - 5$; $\xi_2 = 4\ b - 9$; and $\xi_3 = \frac{C}{15} - 6$.
Equations (4)-(6) provide the results of the additive law equations without fictitious parameter. The corrections have to be applied to equations (4) to (6) from the deviation of the lowest and highest mean values of the output response from the respective grand mean value. The corrections for the thickness variation are -1.5 and 1.6667. The corrections for the surface roughness are -0.00278 and 0.001556. The corrections for film adhesion are -0.23333 and 0.3. Estimates of the thickness $variation(\psi_1)$, surface $roughness(\psi_2)$ and film $adhesion(\psi_3)$ are presented in Table-5. The expected range of $\psi_1,\ \psi_2$ and ψ_3 is arrived by applying the corrections. Test results in Table-5 are within the expected range.
Using the empirical relations (4) to (6), the performance indicators $\psi_1,\ \psi_2$ and ψ_3 are evaluated for all 27 combinations of three spray painting process variables with three levels: $((((A_i,\ B_j,\ C_k),\ k = 1\ to\ 3),\ j = 1\ to\ 3),\ i = 1\ to\ 3)$. Corrections to the performance indicators are applied to get the range of estimates. Figures 2 to 4 show the lower and upper bound estimates of the performance indicators for the full factorial design of experiments. Test data [3] is found to be within/close-to the

estimated range. Table-6 gives the summary of the specific optimal spray painting parameters and the estimates of the performance indicators

Table-5: Estimates of performance indicators (viz., thickness *variation*(ψ_1) , surface *roughness*(ψ_2) , and film *adhesion*(ψ_3)) from empirical relations.

S. No.	Distance, A (mm)	Pressure, B (bar)	Speed, C (mm/s)	Estimates of performance indicators		
				Test [10]	Estimates	Expected Range
Thickness variation, $\psi_1(\mu m)$ Eq.(4)						
1	100	2	75	9	9.167	7.667 – 10.833
2	100	2.25	90	2	0.333	-1.167 – 2 (≤ 2)
3	100	2.5	105	9	10.5	9 – 12.167
4	125	2	90	5.5	7.0	5.5 – 8.667
5	125	2.25	105	5.5	5.667	4.167 – 7.333
6	125	2.5	75	18	16.33	14.833 – 18
7	150	2	105	18	16.33	14.833 – 18
8	150	2.25	75	14	15.5	14 – 17.167
9	150	2.5	90	18	18.17	16.667 – 19.833
Surface roughness, $\psi_2(\mu m)$ Eq.(5)						
1	100	2	75	0.102	0.1008	0.098 – 0.1023
2	100	2.25	90	0.110	0.1128	0.11 – 0.1143
3	100	2.5	105	0.162	0.1604	0.1577 – 0.162
4	125	2	90	0.104	0.1024	0.0997 – 0.104
5	125	2.25	105	0.096	0.0948	0.092 – 0.0963
6	125	2.5	75	0.130	0.1328	0.13 – 0.1343
7	150	2	105	0.083	0.0858	0.083 – 0.0873
8	150	2.25	75	0.070	0.0684	0.0657 – 0.07
9	150	2.5	90	0.137	0.1358	0.133 – 0.1373
Film adhesion, $\psi_3(\%)$ Eq.(6)						
1	100	2	75	96.5	96.57	96.33 – 96.87
2	100	2.25	90	95	95.23	95 – 95.53
3	100	2.5	105	98.5	98.2	97.967 – 98.5
4	125	2	90	97	96.7	96.467 – 97
5	125	2.25	105	97.5	97.57	97.33 – 97.87
6	125	2.5	75	98.5	98.73	98.5 – 99.03
7	150	2	105	98.9	99.13	98.9 – 99.43
8	150	2.25	75	98.5	98.2	97.967 – 98.5
9	150	2.5	90	98.9	98.97	98.733 – 99.27

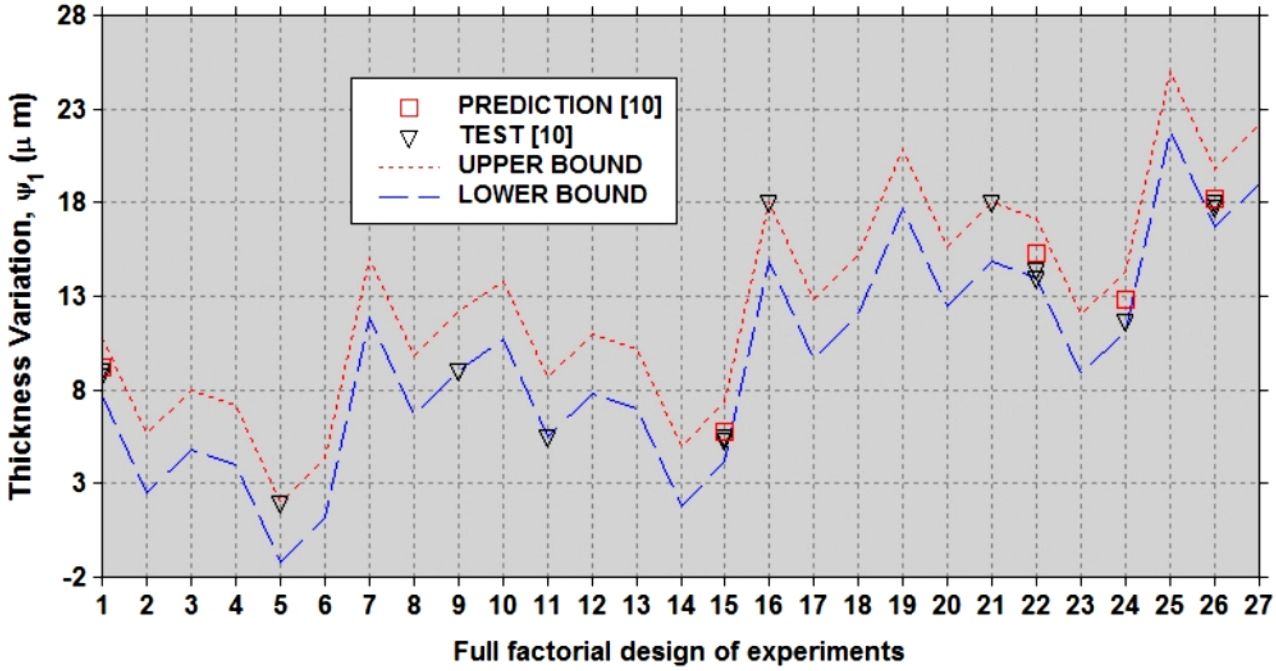

Figure-2: Range of thickness variation estimates for all combinations of 3 spray painting process parameters with 3 levels.

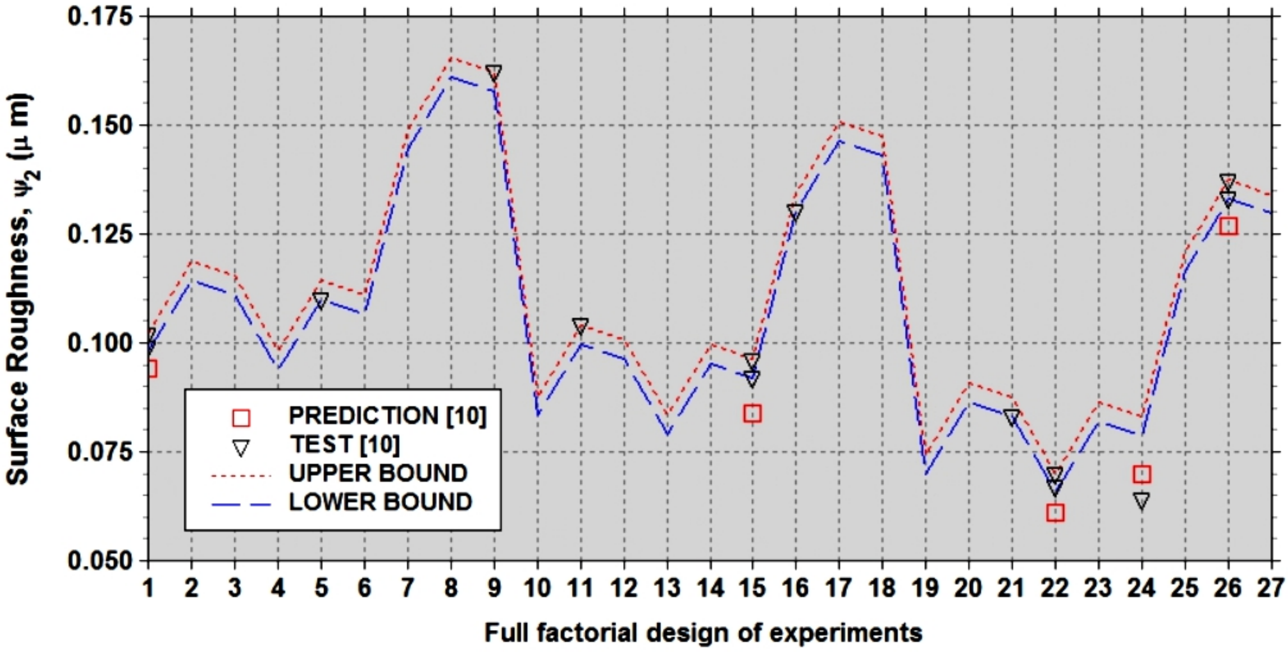

Figure-3: Range of surface roughness estimates for all combinations of 3 spray painting process parameters with 3 levels.

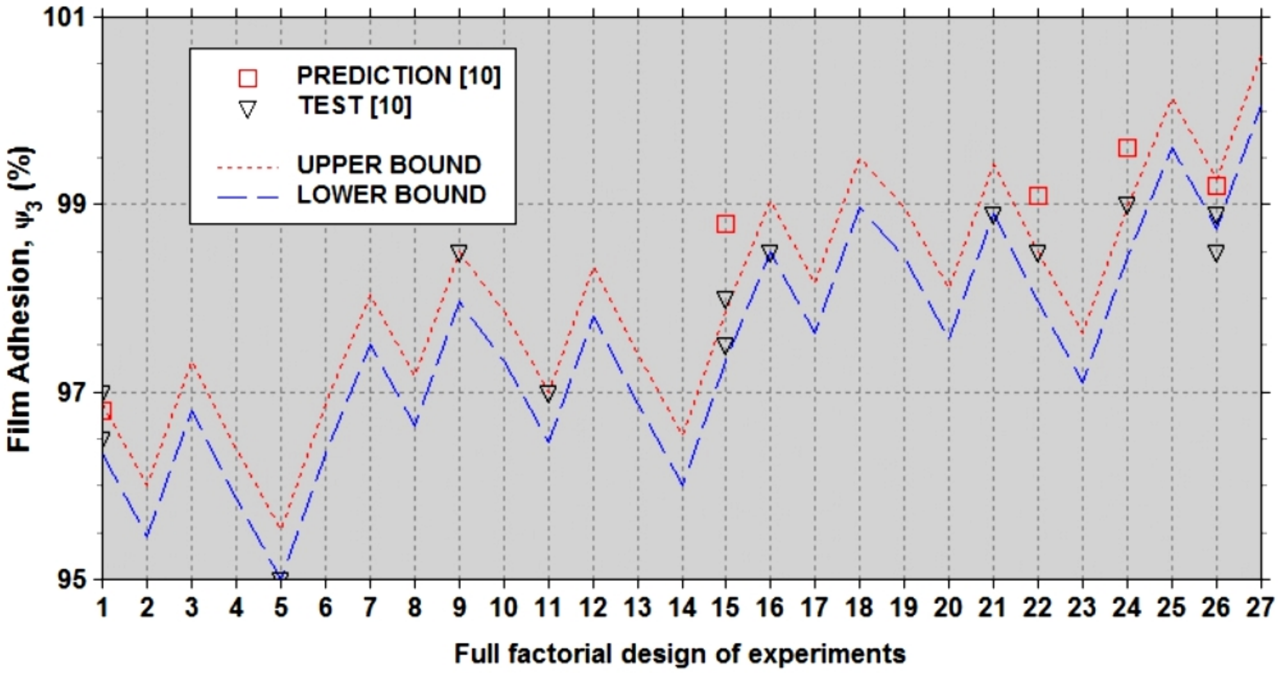

Figure-4: Range of film adhesion estimates for all combinations of 3 spray painting process parameters with 3 levels.

Table-6: Spray painting process parameters for specific conditions and estimates of performance indicators, viz., thickness *variation*(ψ_1), surface *roughness*(ψ_2) , and film *adhesion*(ψ_3) .

Specific conditions	Spray painting process parameters			Thickness variation, ψ_1 (μm)	Surface roughness, ψ_2 (μm)	Film adhesion, ψ_3 (%).
	Distance, A (mm)	Pressure, B (bar)	Speed, C (mm/s)			
Single objective optimization						
$\psi_{1\min}$ ($A_1B_2C_3$)	100	2.25	105	1.6667 - 4.3334	0.1067 – 0.111	96.333 - 96.87
$\psi_{1\max}$ ($A_3B_3C_1$)	150	2.5	75	21.833 – 25	0.1167 – 0.121	99.6 – 100.1
$\psi_{2\min}$ ($A_2B_2C_1$)	125	2.25	75	7 – 10.167	0.079 – 0.0833	96.867 – 97.4
$\psi_{2\max}$ ($A_1B_3C_2$)	100	2.5	90	6.6667 – 9.8334	0.161 – 0.1653	96.633 – 97.17
$\psi_{3\min}$ ($A_1B_2C_2$)	100	2.25	90	≤ 2 (2)+	0.11 – 0.1143 (0.11)	95 – 95.53 (95)
$\psi_{3\max}$ ($A_3B_3C_3$)	150	2.5	105	19 – 22.167	0.1297 – 0.134	100.07 – 100.6
Multi-objective optimization: $\psi_{1\min}$, $\psi_{2\min}$ and $\psi_{3\max}$						
$A_1B_2C_2$	100	2.25	90	≤ 2 (2)+	0.11 – 0.1143 (0.11)	95 – 95.53 (95)

+Test Data [3]

3. Concluding Remarks

Robot spray painting process is being used extensively in automobiles. In order to improve the quality of paint coating, there is a need to specify optimal spray painting process parameters. To accomplish that task, the performance indicators considered in the present study are thickness variation, surface roughness and film adhesion. A simple modified Taguchi approach is followed to identify optimal spray painting process parameters such as distance, pressure and speed and obtain minimum thickness variation, minimum surface roughness and maximum film adhesion. Test data are close-to/within the estimated range. The developed empirical relations for thickness variation, surface roughness and film adhesion will be useful in estimating the performance indicators for the specified spray painting process parameters. There is no need to use any standard software tool based on the statistical regression methodology. It recommends the modified Taguchi method in tracing the optimal spray painting process parameters by representing functionally the dissimilar quality characteristics of multiple responses to a single response characteristic (after non-dimensioning them). There is no need to adopt the S/N ratio transformation. The Taguchi based multi-objective optimization utilized in the present study is quite simple and easy to handle with calculators. Industries prefer simple, reliable and easy to implement procedures while solving practical problems.

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