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TAGUCHI METHOD FOR IMPROVING POWDER COATING PROCESS – A CASE STUDY

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ABSTRACT

Powder coating is widely used in industry to give a product protection from the atmosphere, improve the aesthetics and the surface finish. Electrostatic powder coating process (EPCP) using Corona gun is extensively studied in this work with the perspective of determining operating variables which govern the quality of coat. The parts which were studied were found prone to orange peel defect and were having high dry film thickness (DFT). It was revealed that three controllable process variables namely the applied voltage, powder flow rate and blow air flow rate were responsible for quality of the film coated.

Further the Taguchi method was used to investigate the effects of process parameters on the response characteristics. The effect of each parameter on both response characteristics namely the orange peel defect and DFT was studied using orthogonal array, S/N ratio and ANOVA. Optimal combination of parameters was found for optimum response characteristics. The optimum combination was verified experimentally and it was confirmed that Taguchi method successfully improved the quality of powder coating.

KEYWORDS: Electrostatic Powder Coating Process (EPCP), Dry Film Thickness (DFT), Orange Peel (OP), Design of Experiments (DOE), Taguchi Method, Signal to Noise (S/N) Ratio

INTRODUCTION

Powder Coating

Powder coating has today established itself as the most effective means of metal surface finishing replacing many other commercial finishing techniques like liquid painting and electroplating due to its numerous advantages viz. substantial improvement to chemical corrosion and high mechanical resistance. In powder coating overspray powder can be recycled and thus it is possible to achieve nearly 100% use of the coating powder.

It is a faster process giving better productivity as compared to its competitors. Also the process is environment friendly. For the parts to be used in interiors, the main purpose of powder coating is to enhance the aesthetic of finished parts. This forces the manufacture to produce defect free parts with uniform coating thickness. Powder coated parts are prone to various defects like High or low dry film thickness, Craters, Pinholes, Blistering, Poor Adhesion, Orange peel, Gloss too high, Gloss too low, etc. which are collective output of improper setting of various control parameters.

In present study, a semi automatic system with manual operated corona charging electrostatic spraying gun (Figure 1) is invested for a coating process and it is referred to as an Electrostatic Powder Coating Process (EPCP). The Corona charging method makes use of a high voltage generator to bring an electrostatic charge (mostly negative) onto the powder particles and blow it on to the grounded part with help of booster air.

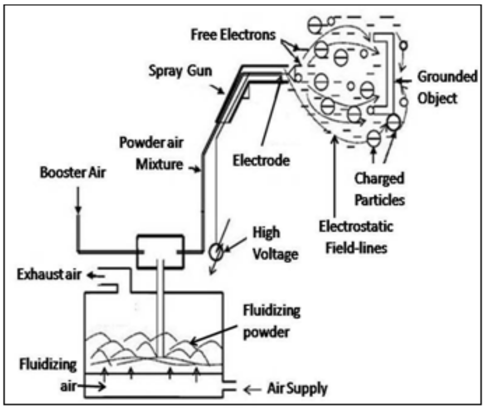

Figure 1: Schematic View of Corona Type Powder Coating System

Taguchi Method

Taguchi method has established itself as an important tool for the robust design in obtaining the high quality process and product which are least sensitive to noise with minimal manufacturing costs. It involves various steps of planning, conducting and evaluating the results of specially designed tables called ‘orthogonal array’ experiments to study entire parameter space with minimum number of trials to determine the optimum levels of control parameters [1].

Taguchi method recommends the use of loss function which is transformed into the S/N ratio to measure the performance characteristic deviating from the desired value and then S/N ratio for each level of process parameters is evaluated based on average S/N ratio response analysis. Greater S/N ratio is corresponding to better quality characteristic irrespective of category. To find which process parameters are statistically significant, Analysis of Variance (ANOVA) to be performed. Finally, a confirmation test is conducted to verify the optimal process parameters obtained from the parameter design [1, 2]. The Taguchi experimental design and analysis to find the optimal combinations of process parameters broadly includes following steps.

Scope of the Work

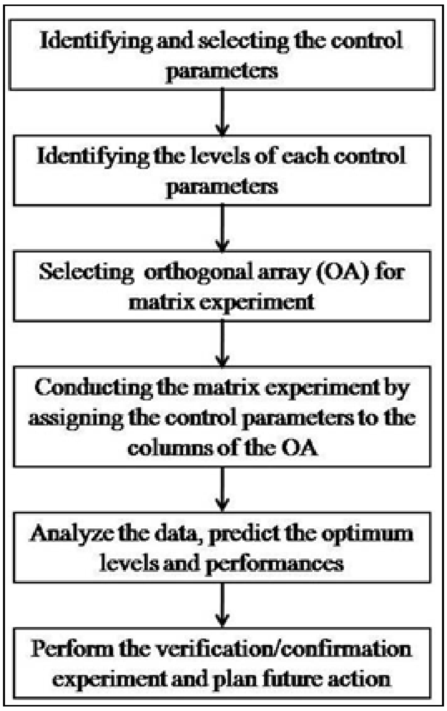

Figure 2: Steps in Taguchi Method

Experimental Procedure

Experimental Set Up

The bed top made of hot rolled steel sheet and pipe, fabricated in a shape shown in figure 3 is selected for study. The half part of the bed top where perforated sheet is welded having size 108 cm x 78 cm is the area considered for experiment. The substrate is first passes through pre-treatment stage prier being powder coated which is then cured in oven. The defects were measured at the five different locations.

Figure 3: The Component (Bed Top)

The part's inspection reports prior conducting the experiments showed that High DFT and Orange peel has the maximum contribution in rejection. By brainstorming with the concerned authorities and experts three control parameters were shortlisted. These parameters with their suggested range are given in Table 1.

Table 1: Process Parameters and Their Ranges

Sr.	Process Parameter	Range	Units
1	Applied voltage	80 – 100	kV
2	Powder Flow Rate	2 - 4	gm / min
3	Booster air flow rate	1.5 - 2.5	gm / cm^3

To add the solidity to the experiment powders from two different supplier's viz. Asian and Nerolac were used.

Taguchi Experimental Design

To conduct the experiment it is desirable to have three minimum levels of process parameters to reflect the true behaviour of output parameters of study. Thus three levels have been assigned to the control parameters and two types of powders became two levels as shown in Table 2.

Table 2: Process Parameters and Their Levels

Factor	Process Parameter	Levels		
		L_1	L_2	L_3
A	Powder	Asian	Nerolac	---
B	Applied voltage	80	90	100
C	Powder Flow Rate	2	3	4
D	Booster air flow rate	1.5	2	2.5

As per Taguchi experimental design philosophy considering all factors, the interaction between powder and applied voltage and overall mean the total degrees of freedom come out to be 10 [2]. Also factor A is of two level, so the nearest mixed level orthogonal array available satisfying the criterion of selecting the OA is L_{18}. For each trial in the L_{18}

array, the levels of the process parameters are indicated in Table 3.

Table 3: L_{18} (2^1 X 3^3) Orthogonal Array with Interaction

Trials	A	B	A x B	C	D
1	1	1	1	1	1
2	1	1	1	2	2
3	1	1	1	3	3
4	1	2	2	1	1
5	1	2	2	2	2
6	1	2	2	3	3
7	1	3	3	1	2
8	1	3	3	2	3
9	1	3	3	3	1
10	2	1	2	1	3
11	2	1	2	2	1
12	2	1	2	3	2
13	2	2	3	1	2
14	2	2	3	2	3
15	2	2	3	3	1
16	2	3	1	1	3
17	2	3	1	2	1
18	2	3	1	3	2

By putting the values of various levels of process parameters from the Table 2 in the Table 3 we get an actual experimental L_{18} (2^1 x 3^3) orthogonal array as given in Table 4

Table 4: L_{18} (2^1 X 3^3) Orthogonal Array with Actual Experimental Levels of Process Parameters

Trials	A	B	C	D
	Powder	Voltage	Powder Flow Rate	Booster Air Flow Rate
1	Asian	80	2	1.5
2	Asian	80	3	2
3	Asian	80	4	2.5
4	Asian	90	2	1.5
5	Asian	90	3	2
6	Asian	90	4	2.5
7	Asian	100	2	2
8	Asian	100	3	2.5
9	Asian	100	4	1.5
10	Nerolac	80	2	2.5
11	Nerolac	80	3	1.5
12	Nerolac	80	4	2
13	Nerolac	90	2	2
14	Nerolac	90	3	2.5
15	Nerolac	90	4	1.5
16	Nerolac	100	2	2.5
17	Nerolac	100	3	1.5
18	Nerolac	100	4	2

Experimental Results

The powder coating experiments were conducted for each set of parameters from trial 1 to trial 18. For each setting of control parameters ten jobs were coated and readings for dry film thickness (DFT) and orange peel were measured at five different locations. The experimental results for average DFT are given in Table 5 and total orange peel are given in Table 6.

Table 5: Experimental Results for Dry Film Thickness

Trials	Dry Film Thickness (Micron)										S/N Ratio
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	
1	60.4	62.2	62.7	61	61.7	60.3	60.4	63.2	59.5	62	34.1699
2	63.4	64.2	64.2	63.5	63.9	64.8	63.6	62.9	65.4	63.8	38.94
3	61.8	62.8	62.9	62.9	64.1	66.1	62	65.2	64.2	65.5	32.5731
4	64	62.9	63.3	63.4	63.7	60.5	63.8	63	64.5	63.5	35.368
5	65.7	63.6	64.8	64.5	64.4	63.5	65	64.5	64.4	64.1	39.9924
6	67.8	68.4	68.4	68.2	68.2	67.2	67.1	67.7	67.5	68.2	42.9517
7	66.4	67	66.7	66.4	65.6	66.5	65.8	66.8	66.4	67.1	42.8542
8	67.1	67.1	67	66.8	67.6	66.6	66.7	66.8	67.1	67.1	47.4353
9	66.6	68.1	65.6	65.4	68.7	68.3	66.5	67.6	67.7	67.2	35.5471
10	62.1	63.4	62.6	62.9	63.3	62.6	63	62.8	62.9	62.7	44.568
11	63.7	64.9	64.4	65.2	63.8	64.2	64.2	63.6	64.1	63.9	41.891
12	65.2	65.3	63.7	65	64.2	64.7	64.1	64.8	65.3	64.2	41.1223
13	61	60.4	61.3	60.9	60.7	62.1	62.3	61.1	60.7	60.9	40.0004
14	65.2	65.3	65.5	65.7	65.8	65.1	65.1	65.1	63.6	63.9	39.0828
15	69.1	70.9	68.1	70.7	70.6	70.5	70.8	66.4	67.5	68.6	32.646
16	66.8	66.7	66.4	66.4	67.2	65.5	67.6	66.6	65.8	67.1	40.4635
17	68.7	70.4	68.5	68.4	67.9	68.3	71	68.5	69	68.1	36.6307
18	72	70.6	71	70.2	70.3	70.9	69.8	71.2	69.3	70.7	39.392

Table 6: Experimental Results for Orange Peel

Trials	Orange Peel (m^2)										S/N Ratio
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	
1	0.047	0.014	0.017	0.045	0.053	0.050	0.065	0.000	0.105	0.036	25.7554
2	0.022	0.054	0.000	0.027	0.000	0.000	0.080	0.000	0.071	0.016	28.0063
3	0.105	0.000	0.022	0.038	0.000	0.000	0.087	0.000	0.000	0.038	26.5825
4	0.104	0.003	0.009	0.008	0.000	0.137	0.018	0.012	0.031	0.000	25.0629
5	0.021	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.000	42.9671
6	0.178	0.220	0.159	0.368	0.143	0.048	0.160	0.111	0.072	0.161	14.7812
7	0.015	0.039	0.036	0.022	0.010	0.029	0.000	0.049	0.000	0.012	31.5416
8	0.207	0.023	0.010	0.016	0.084	0.000	0.000	0.010	0.024	0.021	22.8477
9	0.000	0.149	0.000	0.044	0.037	0.064	0.045	0.037	0.101	0.102	22.7083
10	0.072	0.043	0.160	0.165	0.000	0.073	0.045	0.068	0.056	0.089	20.8148
11	0.107	0.031	0.000	0.000	0.063	0.008	0.000	0.000	0.063	0.000	26.9011
12	0.165	0.072	0.000	0.018	0.032	0.015	0.000	0.014	0.188	0.000	21.5788
13	0.057	0.011	0.041	0.078	0.087	0.102	0.052	0.121	0.218	0.187	18.8956
14	0.000	0.000	0.004	0.007	0.014	0.000	0.000	0.000	0.014	0.000	43.4008
15	0.144	0.316	0.099	0.421	0.151	0.348	0.245	0.018	0.000	0.076	12.8595
16	0.020	0.008	0.011	0.004	0.059	0.000	0.039	0.000	0.000	0.014	32.3665
17	0.249	0.394	0.165	0.178	0.053	0.143	0.446	0.203	0.148	0.083	12.4541
18	0.549	0.446	0.408	0.357	0.339	0.445	0.325	0.500	0.239	0.322	7.89519

ANALYSIS AND DISCUSSIONS OF RESULTS

To study the individual effect of each parameter on dry film thickness and orange peel the average value and S/N ratio of the response characteristics for each variable at different levels were calculated from experimental data. The main effects of process variables both for raw data and S/N data were plotted. The response curves (main effects) are used for examining the parametric effects on the response characteristics. The analysis of variance (ANOVA) of raw data and S/N data was carried out to identify the significant variables and to quantify their effects on the response characteristics. The most favourable values i.e. the optimal settings of process variables in terms of mean response characteristics were established by analysing the response curves and the ANOVA tables.

Dry Film Thickness

The experimental data collected and tabulated in Table 5 is used and the average values of dry film thickness for each parameter at different levels for raw data and S/N data are plotted in Figures 4 and 5 respectively. Figure 4 shows that dry film thickness increases with increase applied voltage and powder flow rate. This is because increasing voltage increases the quantity of charged powder particles and powder flow rate increases the quantity of powder coming out of the coating gun. Both ensure more powder particles sticking to the substrate.

Dry film thickness decreases slightly with Increasing blow air flow rate but it increases again, but its effect is not much significant. The effect of both the powder looks very much same on dry film thickness. Figure 5 shows that S/N ratio increases with increase in applied voltage and blow air flow rate. For powder flow rate it increases first and then decreases. It is clear from the Figures 6 and 7 that there is moderate interaction between powder and applied voltage in affecting the dry film thickness since the responses at different levels of these process parameters are non parallel.

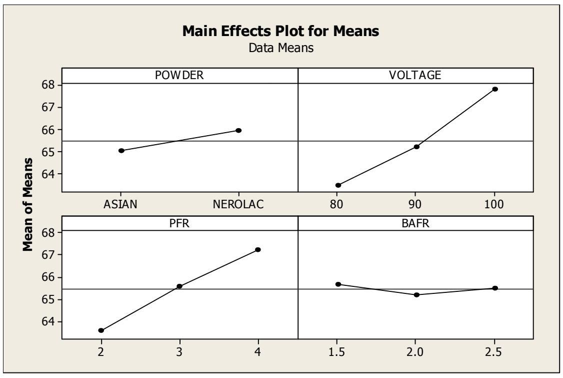

Figure 4: Effects of Process Parameters on Dry Film Thickness (Raw Data)

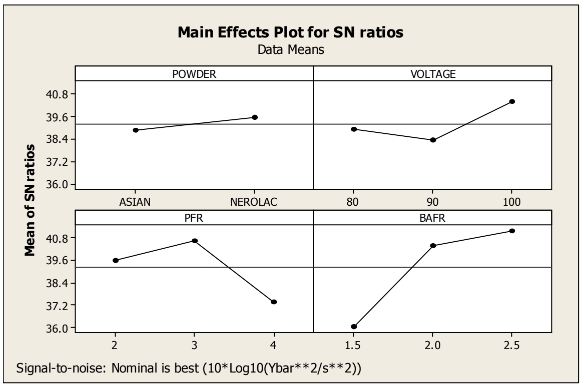

Figure 5: Effects of Process Parameters on Dry Film Thickness (S/N Data)

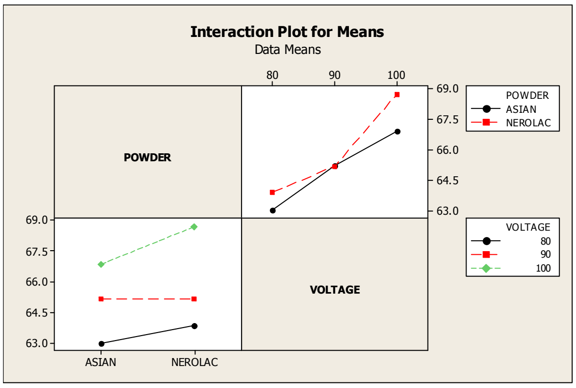

Figure 6: Effects of Process Parameters Interactions on Dry Film Thickness (Raw Data)

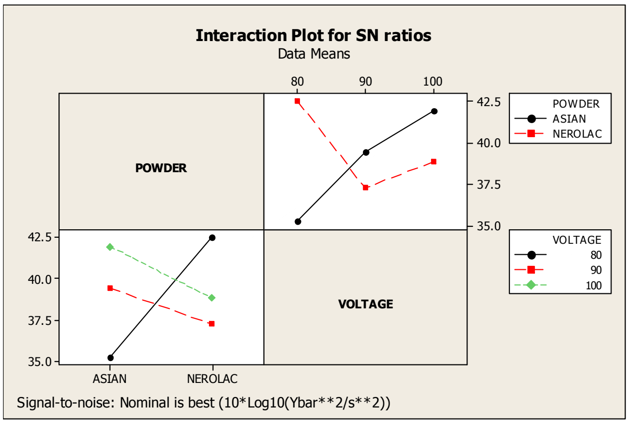

Figure 7: Effects of Process Parameters Interactions on Dry Film Thickness (S/N Data)

Residual plots are used to evaluate the data for the problems like non normality, non random variation, non constant variance, higher-order relationships, and outliers. It can be seen from Figures 8 and 9 that the residuals follow an approximately straight line in normal probability plot and approximate symmetric nature of histogram indicates that the residuals are normally distributed. Residuals possess constant variance as they are scattered randomly around zero in residuals versus the fitted values. Since residuals exhibit no clear pattern, there is no error due to time or data collection order. In order to study the significance of the process variables towards dry film thickness, analysis of variance (ANOVA) was performed. The ANOVA of the S/N data and the raw data for dry film thickness are given in Tables 7 and 8 respectively.

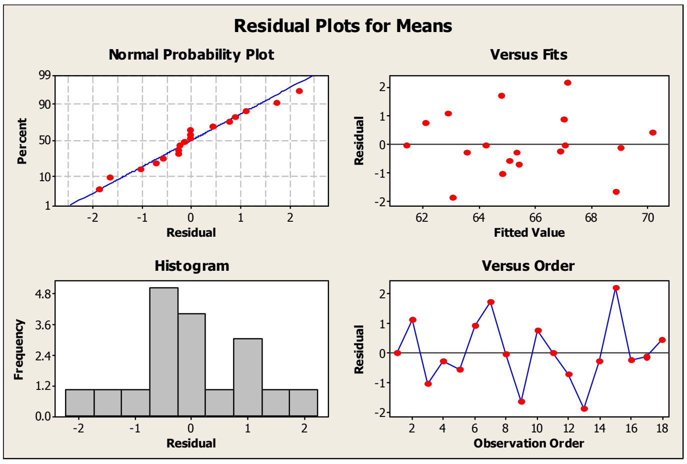

Figure 8: Residual Plots for Dry Film Thickness (Raw Data)

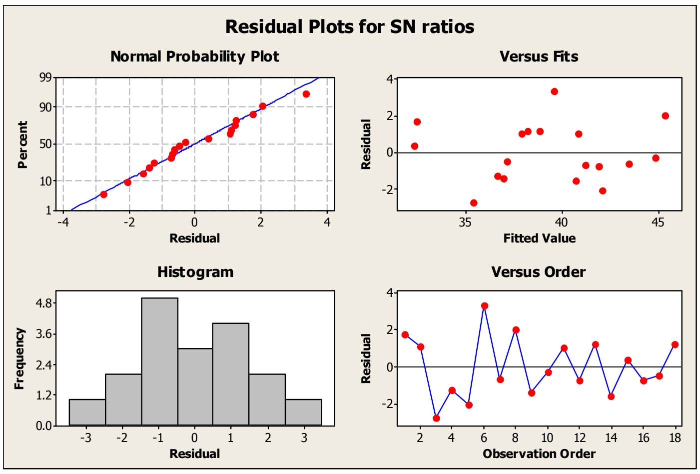

Figure 9: Residual Plots for Dry Film Thickness (S/N Data)

Table 7: Analysis of Variance for Dry Film Thickness (S/N Data)

Source	Df	Seq SS	Adj SS	Adj MS	F	P
POWDER	1	1.977	1.977	1.977	0.36	0.556
VOLTAGE	2	13.515	13.515	6.758	1.23	0.343
PFR	2	33.698	33.698	16.849	3.06	0.103
BAFR	2	91.739	91.739	45.869	8.32	0.011
POWDER*VOLTAGE	2	99.740	99.740	49.870	9.04	0.009
Residual Error	8	44.117	44.117	5.515		
Total	17	284.787				
DF - degrees of freedom, SS - sum of squares, MS - mean squares(Variance), F-ratio of variance of a source to variance of error, P < 0.10 - determines significance of a factor at 95% confidence level						

Table 8: Analysis of Variance for Dry Film Thickness (Raw Data)

Source	Df	Seq SS	Adj SS	Adj MS	F	P
POWDER	1	3.547	3.5467	3.5467	1.48	0.258
VOLTAGE	2	57.003	57.0329	28.5164	11.90	0.004
PFR	2	39.391	39.3915	19.6957	8.22	0.011
BAFR	2	0.710	0.7100	0.3550	0.15	0.865
POWDER*VOLTAGE	2	2.567	2.5673	1.2837	0.54	0.605
Residual Error	8	19.166	19.1660	2.3958		
Total	17	122.414				
DF - degrees of freedom, SS - sum of squares, MS - mean squares(Variance), F-ratio of variance of a source to variance of error, P < 0.10 - determines significance of a factor at 95% confidence level						

From the tables it is clear that voltage, powder flow rate and blow air flow significantly affect both the mean and the variation in the dry film thickness values which is indicated by the bigger values of sum of squares and p-values. The response tables given in Tables 9 and 10 respectively for S/N ratios, means show the average of each response characteristic for each level of each factor. The tables include ranks based on Delta statistics, which compare the relative magnitude of effects. The Delta statistic is the highest minus the lowest average for each factor. Minitab assigns ranks based on Delta values; rank 1 to the highest Delta value, rank 2 to the second highest, and so on.

The ranks and the delta values show that blow air flow rate have the greatest effect on dry film thickness and is followed by powder flow rate, voltage and powder in that order. As dry film thickness is ‘nominal is best’ type quality characteristic, it can be seen from Figure 4 that the second level of voltage (B_2) and powder flow rate (C_2) provides the nominal value of dry film thickness, while blow air flow rate and powder have all the levels pretty close to the nominal value. By the S/N data analysis (Figure 5) it is seen that B_3, C_2 and D_3 has highest S/N ratio while powder seem to be a non contributing parameter. Thus it suggests (A_1 or A_2, B_3, C_2 and D_3) as the best levels for optimum (nominal) dry film thickness in powder coating process.

Table 9: Response Table for Dry Film Thickness (S/N Data)

Level	POWDER	VOLTAGE	PFR	BAFR
1	38.87	38.88	39.57	36.04
2	39.53	38.34	40.66	40.38
3		40.39	37.37	41.18
Delta	0.66	2.05	3.29	5.14
Rank	**4**	**3**	**2**	**1**

Table 10: Response Table for Dry Film Thickness (Raw Data)

Level	POWDER	VOLTAGE	PFR	BAFR
1	65.03	63.46	63.61	65.70
2	65.92	65.18	65.59	65.21
3		67.79	67.23	65.51
Delta	0.89	4.33	3.62	0.48
Rank	**3**	**1**	**2**	**4**

ORANGE PEEL

Using the experimental data collected and tabulated in Table 6 the average values of orange peel for each parameter at different levels for raw data and S/N data are plotted in Figures 10 and 11 respectively. It is clearly seen that orange peel increases with increase in voltage and powder flow rate, but it increase slightly and the decreases with increase in blow air flow rate. Also Nerolac powder seems to be more prone to orange peel compared to Asian powders. Figure 11 shows that initially with increase in voltage and powder flow rate S/N ratio increases, with further increase the S/N ratio declines. While S/N ratio increases continuously with increase in blow air flow rate. Asian powder has higher S/N ratio than Nerolac powders. It is clear from the Figures 12 and 13 that there is moderate interaction between powder and applied voltage in affecting the dry film thickness since the responses at different levels of these process parameters are non parallel. Residual plots do not show any problem in the distribution of the data and model assumptions (Figures 14 and 15)

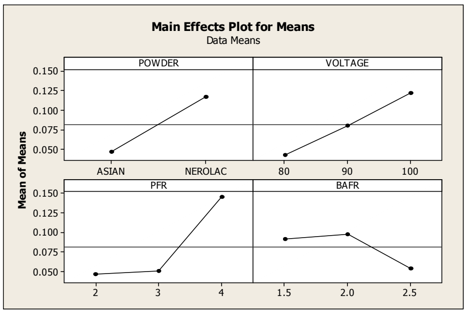

Figure 10: Effects of Process Parameters on Orange Peel (Raw Data)

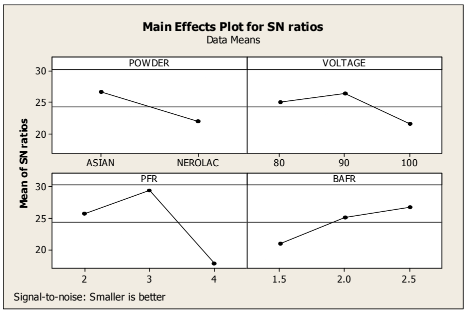

Figure 11: Effects of Process Parameters on Orange Peel (S/N Data)

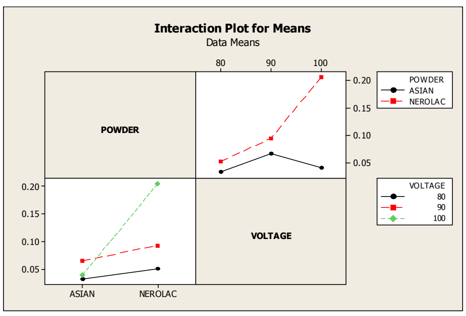

Figure 12: Effects of Process Parameters Interactions on Orange Peel (Raw Data)

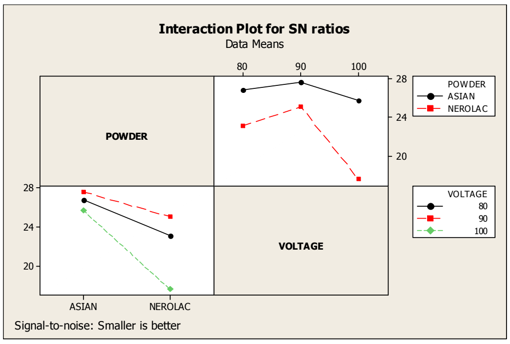

Figure 13: Effects of Process Parameters Interactions on Orange Peel (S/N Data)

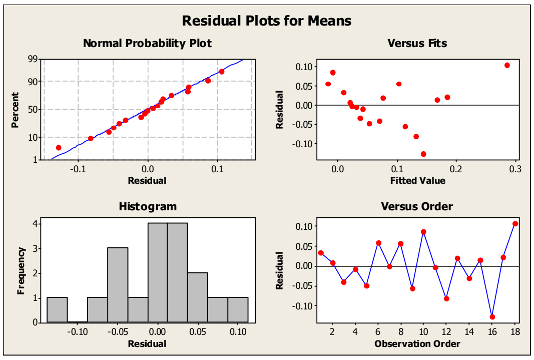

Figure 14: Residual Plots for Orange Peel (Raw Data)

In order to study the significance of the process variables towards orange peel, analysis of variance (ANOVA) was performed. The ANOVA of the S/N data and the raw data for orange peel are given in Tables 11 and 12 respectively. From these tables, it is observed that powder flow rate and voltage significantly affect while blow air flow rate and powder moderately affect both the mean and the variation in the orange peel values. The response tables (Tables 13 and 14) show the average of each response characteristic (S/N data and raw data) for each level of each factor.

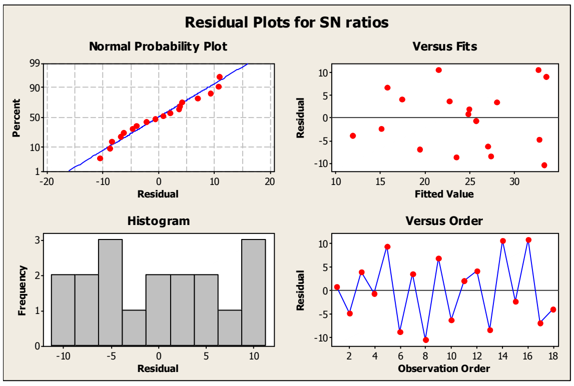

Figure 15: Residual Plots for Orange Peel (S/N Data)

The Tables include ranks based on delta statistics, which compare the relative magnitude of effects. The delta statistic is the highest minus the lowest average for each factor. Minitab assigns ranks based on delta values; rank 1 to the highest delta value, rank 2 to the second highest, and so on. The ranks indicate the relative importance of each factor to the response. The ranks and the delta values for various parameters show that powder flow rate has the greatest effect on orange peel and is followed by blow air flow rate, powder and voltage in that order. As orange peel is the 'lower the better' type quality characteristic, from Figure 10, it can be seen that the first level of powder, i.e. Asian powder (A_1), first level of voltage (B_1), first or second level of powder flow rate (C_1 or C_2) and third level of blow air flow rate (D_3) result in minimum value of orange peel. The S/N ratio analysis (Figure 11) also suggests same levels of the variables except for voltage, but considering the ultimate aim of maximizing S/N ratio, the levels of parameter (A_1, B_2, C_2, D_3) will be the best levels to minimize orange peel.

Table 11: Analysis of Variance for Orange Peel (S/N Data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
POWDER	1	103.14	103.14	103.14	1.02	0.342
VOLTAGE	2	69.73	69.73	34.86	0.35	0.718
PFR	2	428.96	428.96	214.48	2.13	0.182
BAFR	2	108.83	108.83	54.42	0.54	0.603
POWDER*VOLTAGE	2	26.06	26.06	13.03	0.13	0.881
Residual Error	8	806.85	806.85	100.86		
Total	**17**	**1543.56**				
DF - degrees of freedom, SS - sum of squares, MS - mean squares(Variance), F-ratio of variance of a source to variance of error, P < 0.10 - determines significance of a factor at 95% confidence level						

Table 12: Analysis of Variance for Orange Peel (Raw Data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
POWDER	1	0.022447	0.022447	0.022447	3.01	0.121
VOLTAGE	2	0.019178	0.019178	0.009589	1.29	0.328
PFR	2	0.037216	0.037216	0.018608	2.50	0.144
BAFR	2	0.006662	0.006662	0.003331	0.45	0.655
POWDER*VOLTAGE	2	0.020263	0.020263	0.010132	1.36	0.310
Residual Error	8	0.059622	0.059622	0.007453		
Total	**17**	**0.165389**				
DF - degrees of freedom, SS - sum of squares, MS - mean squares(Variance), F-ratio of variance of a source to variance of error, P < 0.10 - determines significance of a factor at 95% confidence level						

Table 13: Response Table for Orange Peel (S/N Data)

Level	POWDER	VOLTAGE	PFR	BAFR
1	26.69	24.94	25.74	20.96
2	21.91	26.33	29.43	25.15
3		21.64	17.73	26.80
Delta	4.79	4.69	11.70	5.84
Rank	**3**	**4**	**1**	**2**

Table 14: Response Table for Orange Peel (Raw Data)

Level	POWDER	VOLTAGE	PFR	BAFR
1	0.04610	0.04232	0.04744	0.09142
2	0.11673	0.07971	0.05112	0.09832
3		0.12222	0.1568	0.05450
Delta	0.07063	0.07990	0.09824	0.04382
Rank	**3**	**2**	**1**	**4**

VALIDATION OF EXPERIMENT

In order to validate the results obtained, ten confirmation experiments were conducted for each of the response characteristics i.e. dry film thickness and orange peel at optimal levels of the process parameters. The average values of the characteristics were obtained and compared with the predicted values. Minitab software was used to predict the values of S/N ratios and mean. The results are given in Table 15. It is to be pointed out that these optimal values are within the specified range of process variables.

Table 15: Predicted Optimal Values and Results of Confirmation Experiments

Performance Measures	Optimum Set of Parameters	Predicted Optimal Value	Actual Value*
Dry Film Thickness	A_1, B_3, C_2, D_3(Asian, 100, 3, 2.5)	67.03 micron	68.48 micron
Orange Peel	A_1, B_2, C_2, D_3(Asian, 90, 3, 2.5)	0.0085 m^2	0.02 m^2

*Average reading of ten conformation Experiments

CONCLUSIONS

Based on the experimental results, S/N and ANOVA analysis performed, the following conclusions have been arrived to obtain optimal process parameters to achieve better surface finish characteristics for powder coating process improvement:

- Based on the illustrations, it is clear that factorial design experiments and Taguchi methods can effectively be used for control of variables that affect the quality of powder coated parts.
- The effects of the process parameters viz. applied voltage, powder flow rate, blow air flow rate and powder, on response characteristics viz. dry film thickness and orange peel, were studied.
- All the process parameters considered for analysis has significant impact on the response characteristics.
- The optimal sets of process parameters were obtained for various performance measures using Taguchi’s design of experiment methodology. The optimal values of process parameters brought the dry film thickness within the desired range and considerably reduced the orange peel.
- It is noticed that, there was a good agreement between estimated and actual values obtained in respect of dry film thickness and orange peel within the preferred significant level.

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