The Application of an Experimental Design for the Defect Reduction of Electrodeposition Painting on Stainless Steel Washers

Chansiri Singhtaun, and Nattaporn Prasartthong

Abstract—The purpose of this research is to reduce the amount of incomplete coating of stainless steel washers in the electrodeposition painting process by using an experimental design technique. The surface preparation was found to be a major cause of painted surface quality. The influence of pretreating and painting process parameters, which are cleaning time, chemical concentration and shape of hanger were studied. A 2^3 factorial design with two replications was performed. The analysis of variance for the designed experiment showed the great influence of cleaning time and shape of hanger. From this study, optimized cleaning time was determined and a newly designed electrical conductive hanger was proved to be superior to the original one. The experimental verification results showed that the amount of incomplete coating defects decreased from 4% to 1.02% and operation cost decreased by 10.5%.

Keywords—Defect reduction, design of experiments, electrodeposition painting, stainless steel.

I. INTRODUCTION

ELECTRODEPOSITION painting or electrocoating is an effective painting method for numerous industrial applications. It is superior to other methods (smearing, spraying, and electrostatic spraying) in that it forms uniformly thick coats on all surfaces of workpieces including extreme recess areas. Another advantage is the extremely low level of emission of vapors of volatile organic compounds. Finally the cost of operating an electrocoating tank is lower than that of any other painting method [1].

Electrocoating is a dip coating process. The process uses paint particles suspended in a fluid bath. An opposite charged substrate is lowered into the paint bath and the paint particles are attracted to the substrate. The paint particles build up on surfaces and form an even continuous film over the entire surface. In general, the overall process consists of four main process steps: pretreating, electrocoating, rinsing, and baking.

The electrocoating process may be anodic or cathodic depending on the charge applied to the substrate. Although the processes are almost the same, the properties of the resultant coating are dissimilar. Anodic electrocoating applies paint to positively charged substrates. The negatively charged paint particles are deposited onto the substrate (anode). One disadvantage of this process is that metal substrates dissolve

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and become included into the coating, which affects surface properties. Cathodic systems deposit paint onto negatively charged substrates and offer several advantages over anodic systems. For example, metal dissolution of the substrate does not occur, contamination in the paint bath is reduced, corrosion resistance is improved, and a better color consistency occurs [2].

Electrocoating on stainless steel, titanium and refractory metals is difficult due to the rapid and spontaneous formation of superficial oxide films [3]. Moreover, stainless steel is relatively inert; hence the adhesion of paints and coatings is often a problem. Pretreatment is considered as an important process to enhance adhesion [4]. Studies of appropriate electrocoating conditions for several coating materials on various substrates have been well researched by using experimental design techniques such as [5], [6]. However, the study of electrocoating on stainless steel is limited.

Experimental design is a critically important tool for process improvement, manufacturing process development, and new product design. In general, the objectives of the experiment may include determining which input variables are most influential on the output response or determining where to set the influential input variables so that the output response is close to the desired nominal value, or the variability in the output response is small. Factorial designs are the most efficient technique for the experiments involving the study of the effects of two or more factors. In each replication of the experiment, all possible combinations of the levels of the factors are investigated. Therefore, both of the main effects of the variables and their interactions are examined [7].

To test the significance of both the main effects and their interactions, the corresponding mean square is divided by the error mean square. Large values of this ratio imply that the corresponding treatment significantly affects the output response. For computation, there are many statistical software packages such as MINITAB, SPSS, etc. to conduct analysis of variance (ANOVA). Graphs of the main effect and interaction plot provided by the software package are helpful to assist in interpreting the results of the experiments and in determining the level of significant variables.

Furthermore, fitting a response surface to the levels of quantitative factors is useful so that the researcher has an equation that relates the response at various combinations of the factors. This equation can be used for predicting the response at factor levels between those actually used in the experiment.

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In this work, we investigate the cause of incomplete coating defects of cathodic electrocoating on stainless steel washers in a case study company. The influence of stainless steel surface preparation and electrocoating parameters are examined. The study is carried out by using a 2^3 full factorial design. The optimal composition of parameters to minimize amount of incomplete coating defects is evaluated.

II. METHODOLOGY

A. Problem Definition and Data Collection

There are five main electrocoating defects in the case study company as shown in Fig. 1.

Fig. 1 Types of electrocoating defects

The defects corresponding to the number shown in Fig. 1 are incomplete coating, roughness, thin coating, part sticking, and stain, respectively. The number of defects classified by type is collected and illustrated in a Pareto chart (see Fig. 2) so that we can identify the main problems to solve. Fig. 2 shows that the incomplete coating defect is the main problem, which covers over 40% of overall defects, which is 4% of the production volume.
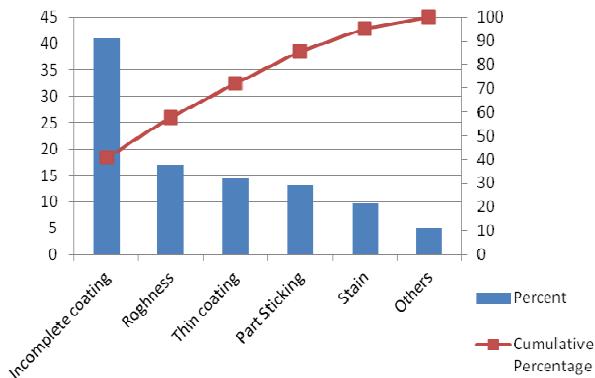

Fig. 2 Pareto chart of electrocoating defects

B. Problem Analysis

To analyze the input variables or factors that might affect the coating performance and quality, the process is observed thoroughly. The overall process consists of four main steps: pretreating, electrocoating, rinsing, and baking.

By analyzing the cause and effect diagram, three factors that can cause incomplete coating defects are selected from the pretreating, and electrocoating steps. The pretreating step, where the objective is to remove grease on the surface and prepare the surface for coating, may impact the paint adhesion. Two selected factors in this process are cleaning time and chemical concentration. Two levels of each factor are tested based on production and cost constraints. The cleaning time cannot be increased to over 5 minutes because production volumes will not meet production targets. Thus, the tested cleaning time ranges between 30-35 minutes. The chemical concentration level is determined to fit with the maximum allowable additional chemical solution cost. Therefore, the chemical concentration used in the experiments ranges from 5.0-5.5%.

The other factor is obtained from product investigation. Due to the low electrical conductivity performance of stainless steel, it may be difficult to make paint deposits on the workpieces. In addition, the non-coating of defective products usually occurs at the area that is in contact with the electrical conductive hanger. Therefore, the appropriate shape of the hanger is considered. Because the present design of the hanger has a shallow groove, the washers hanging on it can float and collide with other parts of the hanger when it is dipped into the electrocoating bath. The new hanger is designed to solve this problem without a change in working procedure. The same material, which is aluminum, is still used. The new shape of hanger is almost the same as the original hanger but its groove is 2 millimeters deeper in order to lock the washers and increase the electrical conductivity simultaneously. Both hangers are illustrated in Fig. 3.
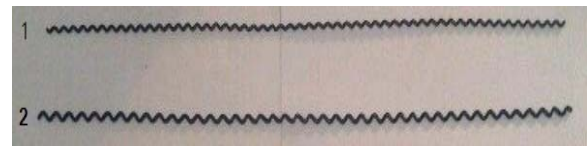

Fig. 3 Original and new design hanger

To calculate the increase in electrical conductivity of a new hanger, the electrical conductivity of aluminum ($\sigma = 0.377 \times 10^6 \Omega^{-1} \cdot cm^{-1}$) is multiplied by the additional length. There are 95 grooves per hanger and each groove has an incremental 0.4 centimeter length. The new hanger increases electrical conductivity by $14.326 \times 10^6 \Omega^{-1}$.

To summarize, the three factors and the test levels are presented in Table I.

C. Experimental Design and Implementation

A 2^3 full factorial design with two replications is used to carry out the experiment to test the two following hypotheses. The first hypothesis is to test whether factors (treatments) affect the response:

TABLE I
LOW LEVEL AND HIGH LEVEL VALUES OF THE FACTORS

Factors	Low Level (-1) (Present Condition)	High Level (+1) (New Condition)
A:cleaning time (minutes)	30	35
B: chemical concentration (%)	5.0	5.5
C: shape of hanger	original shape	new shape

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H_0: There is no treatment effect
H_1: There is at least one main treatment effect

The other hypothesis is to determine whether treatments interact:

H_0: There is no treatment interaction
H_1: There is at least one treatment interaction

In each set of treatments, one batch of washers, which is composed of 950 washers (95 pieces per hanger and 10 hangers per batch), is used. The number of incomplete coated washers is counted as a response (Y). The run order for each set of treatments is created randomly by using the "create factorial design" function in MINITAB. The results of the experiments are statistically analyzed by using analysis of variance at a level of significance $\alpha = 0.05$. After that, the experimental results are interpreted and the optimal combination of factors is set.

D. Experimental Verification

Before using the optimal combination as a working standard, another set of experiments is performed to verify the replicability of the experiment.

III. RESULTS AND DISCUSSION

This part is divided into three sections. It starts with the experimental results and interpretation of results. The next section shows the results of experiment verification. Finally, the last section shows the effect of changes in production conditions on operation cost.

A. The Experimental Results and Analysis

The number of incomplete coated washers of 16-run experiments are summarized in Table II.

TABLE II
THE NUMBER OF INCOMPLETE COATED WASHERS (PIECES) FOR THE EXPERIMENT

Shape of Hanger (C)	Cleaning Time (A)			
	30 minutes		35 minutes	
	Chemical Concentration (B)		Chemical Concentration (B)	
	5.0%	5.5%	5.0%	5.5%
original	37	33	20	30
shape	36	40	25	30
new	25	35	13	13
shape	30	30	10	11

Before making a conclusion from the ANOVA table, the assumption of experimental or residual error, which is normal and independently distributed, should be examined by analyzing the residual plots illustrated in Fig. 4.
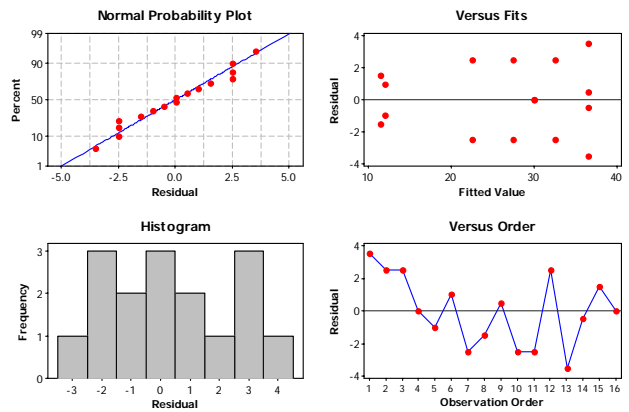

Fig. 4 Residual plots for response (Y)

From Fig. 4, the Normal Probability Plot shows that the residuals are in linear form. It can be concluded that the data distribution is a normal distribution. Likewise, the Histogram shape also shows that the data distribution is normal. The two upside down bell shapes may stem from the two different shapes of hanger. The other two graphs show that the residual is independently distributed because the plotted data is distributed randomly. Thus, it can be concluded that the residual is normal and independently distributed. After assumption verification, the ANOVA table for the experiment summarized in Table III is considered.

TABLE III
ANOVA FOR THE NUMBER OF INCOMPLETE COATED WASHERS RESPONSE (Y)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	P-Value
A	1	812.25	812.250	94.17	0.000
B	1	42.25	42.250	4.90	0.058
C	1	441.00	441.000	51.13	0.000
A*B	1	2.25	2.250	0.26	0.623
A*C	1	64.00	64.000	7.42	0.026
B*C	1	1.00	1.000	0.12	0.742
Residual Error	8	69.00	8.625		
Pure Error	8	69.00	8.625		
Total	15	1467.75			

From Table III, the factors A, C, and AC interaction significantly affect the response because p-values are less than the level of significance $\alpha = 0.05$. Because AC interaction has a significant effect, only the AC interaction plot (shown in Fig. 5) is used and the main effect plots are ignored to set the level of factors. The main effect plot of factor B (shown in Fig. 6) is also considered to determine the level of factor B.

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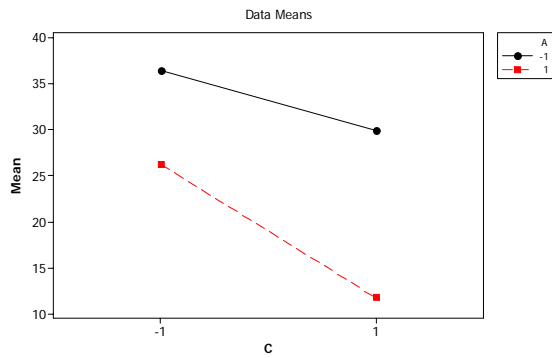Vol:6, No:10, 2012

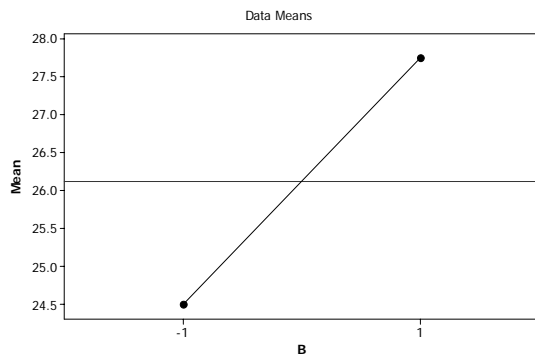Fig.5 AC interaction plot for mean response (Y)

Fig. 6 Main effect plot of factor B for mean response (Y)

According to Fig. 5 and Fig. 6, factors A and C should be set at high levels while factor B should set at a low level in order to minimize the number of incomplete coated washers. In other words, the appropriate pretreatment condition is using 5.0% chemical concentration to clean washers for 35 minutes, and, the new shape of hanger is recommended.

B. Results of Experimental Verification

To verify the repeatability of the results, another set of experiments where factors A and C are at high levels, and factor B is at a low level is conducted. The following hypotheses are tested:

$$H_0: \mu > 11$$
$$H_1: \mu < 11$$

The hypothesis testing is set to verify that the mean of the number of incomplete coated washers (μ) is not greater than the average number of incomplete coated washers in the former experiments (see Table II) when all factors are set at the same level. The average number of incomplete coated washers at that level was $(13+10)/2 = 11.5$. Ten runs of the experiments are done. In accordance with the t-test results (shown in Table IV), p-value = 0.048 is less than the

significance level $\alpha = 0.05$. This means the revised setting conditions are confirmed not to make the incomplete coating defects over 11 pieces or 1.16% of production volume.

TABLE IV
ONE-SAMPLE t-TEST: THE NUMBER OF INCOMPLETE COATED WASHERS
(Y)

Variable	N	Mean	Standard Deviation	Standard Error of Mean	95% Upper Bound	T	P-Value
Y	10	9.700	2.214	0.700	10.983	-1.86	0.048

C. Calculation of Change in Operation Cost

Because the company wants to minimize the number of incomplete coated washers, we recommend using a high level of cleaning time (35 minutes), a low level of chemical concentration (5.0%) and the new design of the hanger. The recommended process condition gives average incomplete coated washers = 9.7 pieces or 1.02% (see Table IV). The rework cost decreases by 19,878.75 baht/month.

However, setting the cleaning time at a higher level leads to additional production time and cost. When increasing the cleaning time by 5 minutes/batch, the company requires 143 rounds/month more than the present condition in order to reach the production target (3,000 rounds/month). This causes incremental operation cost (labor cost, facility cost, infrastructure cost, etc.) by 3,150 baht/month. The new design hanger is 2 baht more expensive than the original hanger and 1,000 hangers are required for three pretreatment baths. On average, the life time of the hanger is 2 years. Thus, there is additional expense of hangers at 84 baht/month.

In conclusion, setting the recommended production condition can reduce operation cost by 16,644.75 baht/month or 10.5%.

IV. CONCLUSION

The performance of electrocoating on stainless steel washers can be enhanced by carefully preparing the surface and by increasing the electrical conductivity of the hanger. Pretreating performance can be improved by spending more time cleaning the substrates without a chemical concentration increase. However, the process parameters and the tested level in this work were set under company constraints. The results can be applied only to the similar process.

For future research, this work can be extended to working standards and manuals for general electrocoating on stainless steel. The various parameters, such as the shape of stainless steel workpieces, the type of chemical solution, the electrical applications, etc. should be investigated under general electrocoating applications.

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