STATISTICAL MODELING OF ZINC ELECTROPLATING PARAMETERS ON MILD STEEL

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Abstract- **In this paper an empirical model of zinc electroplating parameters were developed to predict the coating thickness T_c (μm) and Hardness H (VHN) of zinc layer on Mild steel. Response surface methodology has been used for statistical analysis and models adequacy were confirmed with the help of Anova results. Graphical representations have been used for exploring and analyzing the responses in order to identify the main, quadratic and interaction effects. To this end, optimum conditions of process parameters were revealed and voltage of 1.0 volts, plating time of 29.25 min and distance between the cathode to anode of 10.4 cm provides maximum coating thickness and hardness.**

Keywords- **zinc electroplating, response surface methodology, Anova table, Design Expert 8.0.1.**

I. INTRODUCTION

Non-coated steel has no place in any structural application because of its high corrosiveness, but it is good if the corrosive resistance was increased. Zinc coating protects the steel from corrosion and improves the service span because zinc is more anodic than steel owing to this zinc metal corrodes before than steel [1-3].Zinc can be coated on steel either by hot dipping or electroplating process [2]. As compared to hot dipping process electroplating process produces thin zinc coating which is essential for some structural applications and metal joining techniques. Zinc electroplating can be done by alkaline bath, cyanide bath, non – cyanide bath and acid bath [10] but in recent decade's acid bath have been used in all fields because it is readily available and less harm than cyanide baths [1,4]. Although, proper selection of plating parameters can give better coating with good surface finish that will exhibit high degree of corrosion resistance and mechanical properties [9,11].

In past decades, many research works have been carried out to reveal the effect of process variables on electroplating, most of the investigations dealt with the ancient methodology of experimentation in which interaction effect of process variables on response could not be considered and this may lead to the counterfeit optimal conditions. In order to overcome the above said hindrance the response surface methodology could be used because Response surface methodology is most efficient statistical tool for solving the multi - variable and multi – response problems [5, 6]. In detailed literature survey, no research papers were found in statistical modeling of Zinc electroplating process parameters. Therefore, to bridge the research gap this investigation was carried out in statistical modeling and multi - response optimization of zinc electroplating process parameters on coating thickness and hardness.

II. PLAN OF INVESTIGATION

This research work was planned to carry out in following steps:

- Identifying the important independent process parameters
- Finding the upper and lower limits of independent process parameters
- Developing the design matrix
- Conducting experiments according to the design matrix
- Recording the responses
- Developing the mathematical models
- Calculating the model coefficients.
- Testing the adequacy of models
- Analysis of results
- Presenting the main and interaction effects of process parameters in graphical form and Discussion

A. Identifying the Important Independent Process Parameters

Voltage, anode to cathode distance and plating time were identified as important electroplating parameters for the reason that insufficient plating voltage leads to non-uniform coating and excessive voltage produces dull surface and poor deposition [3]. More gaps between anode and cathode results lack of adhesion, non-uniform coating and more pores on the coating layer and less gap may cause unnecessary coating thickness. Plating time is directly proportional to the coating thickness so optimum plating time is required.

B. Finding the upper and lower limits of independent process parameters

Trials were carried out by varying one of the electroplating parameter whilst keeping other parameters as constant. The parameters range was decide by inspecting the trail specimen for uniform coating, good adhesion and brightness. Table.1 shows the working parameter range.

Parameter	unit	Notation	Lower limit	Upper limit
Voltage	Volts	V	0.5	1.0
Distance between cathode to anode	Cm	D	10	30
Plating time	min	T	10	35

Table.1 Electroplating parameters and limits

C. Developing the design matrix

Design Expert 8.0.1 was used to develop the design matrix and further analysis. Response surface methodology has been chosen to carry out the experiments.

D. Conducting experiments according to the design matrix

Mild steel dimension [1] of 10 x 30 x 2 mm and pure zinc rod was used as cathode, anode respectively and Standard zinc electroplating bath [7] was used to conduct the experiments, bath chemical compositions were shown in Table 2. Electroplating process was carried out in three distinct stages: Pre-plating, Plating process and post plating process. In pre-plating stage mild steel specimens were polished with emery sheets of 60, 120, 360, 400 grades successively and with emery cloth. Polished specimens were rinsed in distilled water and then in acetone afterwards specimens were dried. Finally the prepared samples were stored in desiccators until they were needed for the experiments.

Bath component	Value (gm/Liter)
$ZnSo_4.7H_2O$	225
Na_2So_4	30
NaCl	15

Table.2 Standard zinc bath composition

After Pre-plating stage mild steel and pure zinc specimen were immersed into the standard zinc bath and mild steel was connected to the negative terminal and pure zinc rod was connected to the positive terminal of the Mega Tech 0-30volt power supply and experiments were conducted according to the developed design matrix shown in Table.3. Finally in post plating process the specimens were rinsed with distilled water and dried.

E. Recording the responses

Coating thickness was taken at seven different locations from each specimen in order to determine the average coating thickness using PosiTector 6000 – DeFesko Analyzer, based on non-destructive physical method and hardness was measured using portable digital hardness tester. In this research work, three design variables are considered and hence the design matrix is a three factor D-optimal design consisting of 22 sets of experimental values. These 22 sets of experimental values are used as the database for response surface methodology to develop a mathematical model for prediction of the response.

F. Developing the mathematical models

The response function representing any of the electroplating outcomes can be expressed as Y = f (V, D, T) where Y is the yield. The second order polynomial regression equation is used to represent the response surface for K factors and is given by equation 1.

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x^2{}_i + \sum_{\substack{i,j=1 \\ i \neq j}}^{k} b_{ij} x_i x_j \text{ ------ } 1$$

Where b0 is the free term of the regression equation; the coefficients b_1, b_2... b_k are linear terms; b_{11}, b_{22}... b_{kk} are the quadratic terms; and b_{12}, b_{13}... b_{k-1}, k are the interaction terms. For three factors, the selected polynomial could be expressed as

Y = b0+ b1 V +b2 D + b3 T + b11 V2 + b22 D2 + b33 T2+ b12 VD + b13 DT + b23 VT + b123 VDT ------ 2

G. Calculating the coefficient of models

The coefficient values of Equation.2 were calculated by regression method and are presented in the Table 3. Design Expert 8.0.1 software package was used to calculate the coefficients value. The significance of the coefficients was evaluated and insignificant coefficients were not included in the final model.

Co-efficient	Coating Thickness, T_c (µm)	Hardness, H (VHN)
b_0	0.672	116.698
b_1	- 1.736	- 65.521
b_2	0.011	- 0.556
b_3	-4.642×10^{-3}	- 0.010
b_{11}	1.044	42.969
b_{22}	-1.795×10^{-5}	- 0.025
b_{33}	-3.140×10^{-5}	- 6.665
b_{12}	- 0.042	- 0.068
b_{13}	-3.257×10^{-4}	- 0.013
b_{23}	0.065	2.012
b_{123}	-7.073×10^{-4}	- 0.019

Table.3 Coefficient values of models

Response	Sum of Squares	Degrees of freedom	R - square Value	Adjust R - Square value	F-Ratio	P value Prob > F	Adequacy of the model
Coating Thickness	0.16	16	0.98	0.94	22.35	0.0014	Significant
Hardness	0.85	16	0.99	0.96	35.25	0.0005	Significant

Developed model is significant if the P – value is less than 0.05 at 95% of confidence level.

Table.4 ANOVA results

Following equations are the final mathematical model of coating thickness T_c (μm) and Hardness H (VHN).

Coating thickness (T_c) = $0.672 – 1.736 V – 0.011 D – (4.642 \times 10^{-3} T) + 1.044 V^2 – (1.795 \times 10^{-5} D^2) – (3.140 \times 10^{-5} T^2) - 0.042 VD – (3.257 \times 10^{-4} DT) + 0.065 VT – (7.073 \times 10^{-4} VDT)$ ----- **3**

Hardness (H) = $116.698 - 65.521 V – 0.556 D – 0.010 T + 42.969 V^2 – 0.025D^2 – 6.665 T^2 - 0.068 VD -0.013 DT + 2.012 VT - 0.019 VDT$ --------- **4**

H. Testing the adequacy of models

The adequacy of the models was tested using the analysis of variance (ANOVA) technique [6, 8]. According to this technique, the calculated P-value should not exceed 0.05 for a desired confidence level say 95 %. Table.5 is evident that the models are adequate. The scatter diagram depicted in Fig.1 & 2 shows that the experimental values and the values calculated from mathematical models are in good covenant.

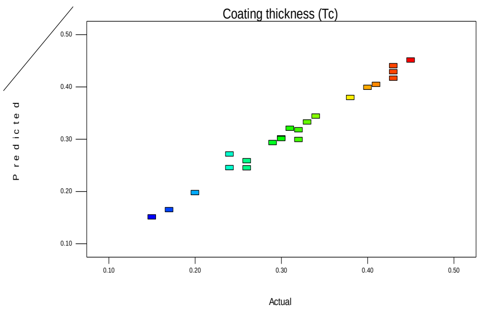

Fig.1 Experimental and Theoretical Values of Coating thickness

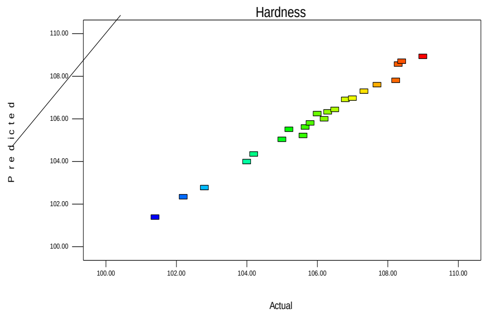

Fig.2 Experimental and Theoretical Values of Hardness

I. Analysis of the result

The developed final mathematical models can be employed to predict the coating thickness T_c (μm) and Hardness H (VHN) of zinc electroplating on steel for the range of parameters used in this investigation and it can also be used to calculate the main and interaction effect of process parameters on above said responses. Similarly, by substituting the desired values of coating thickness and Hardness in the developed model, it is possible to find out the parameters value that has to be controlled during electroplating.

III. Presenting the Main and Interaction Effects of Process Parameters in Graphical Form and Discussion

A. Main effect of voltage on coating thickness

Fig.3 shows that coating thickness increases with respect to voltage rise but in the range of 0.5 to 0.7 voltages there is a slight drop in thickness curve this is due to the fact that zinc ionization capability is less in that voltage ranges and beyond the 0.7 voltage zinc ionization becomes direct proportion to the respective voltage. Similarly harness increases with respect to coating thickness Fig.4 are evident for that phenomenon.

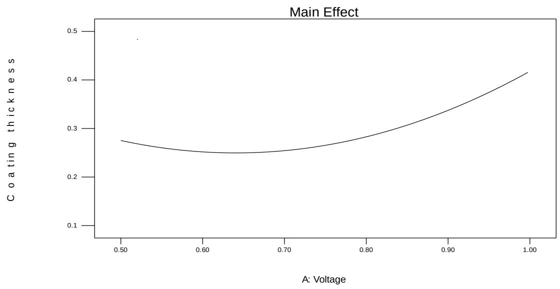

Fig.3 Main Effect of Voltage on Coating thickness

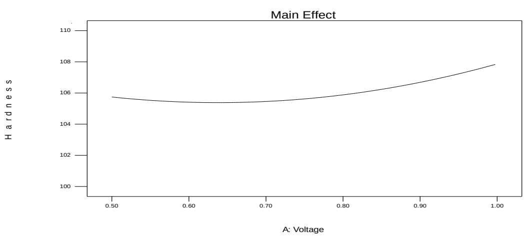

Fig.4 Main Effect of Voltage on Hardness

B. Main effect of Anode to cathode distance on coating thickness

Fig. 5 & 6 increases in cathode to anode distance decreases zinc coating hardness this is due to the fact that gradual decrease in coating thickness with respect to distance between the electrodes because hardness and coating thickness both are in direct proportion.

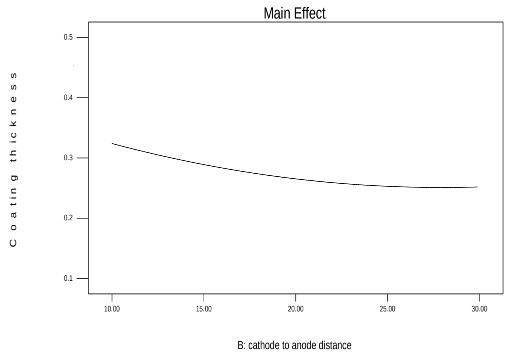

Fig.5 Main Effect of Anode to Cathode Distance on Coating Thickness

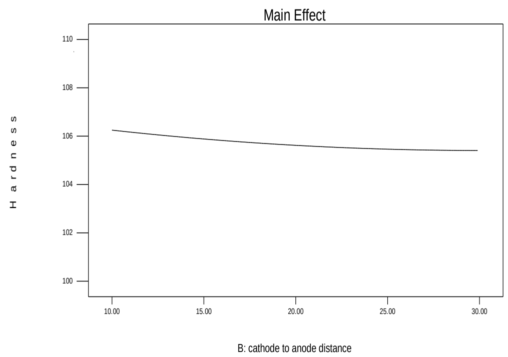

Fig.6 Main Effect of Anode to Cathode Distance on Hardness

C. Main effect of plating time on coating thickness

It is clear from Fig.7 & 8 coating thickness and hardness are increasing gradually with increase in plating time for the reason that more plating allows more zinc metal to deposit on target material.

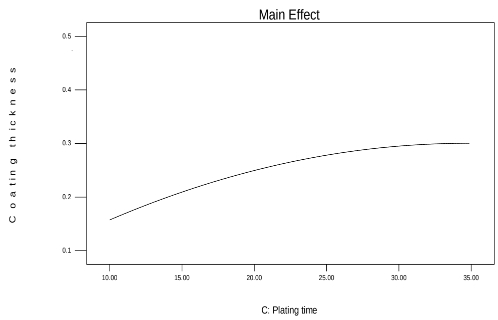

Fig.7 Main Effect of Plating Time on Coating Thickness

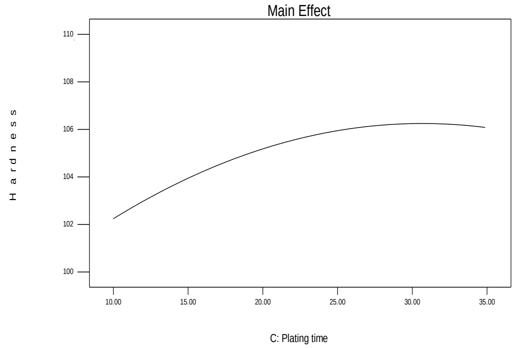

Fig.8 Main Effect of Plating Time on Hardness

D. Interaction effect of voltage, Cathode to anode distance on coating thickness

Fig.9 shows interaction effect of voltage and distance between cathodes to anode. At maximum voltage and in studied range of electrode distance zinc layer thickness was high because zinc transfer rate is high and its ability to reach the target material is well enough. In low voltage zinc ionization capability is less due to this fact zinc layer thickness is thin.

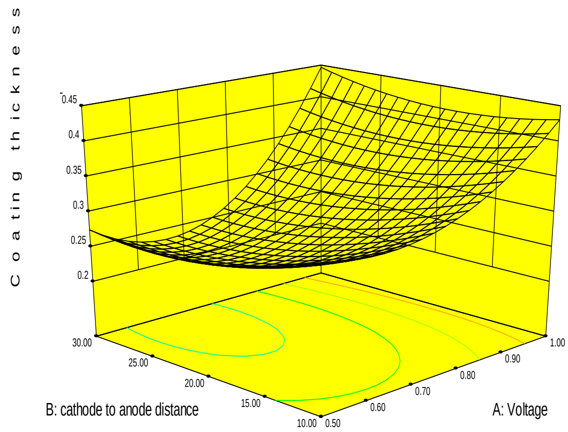

Fig.9 Interaction effect of voltage, Cathode to Anode Distance on Coating Thickness

E. Interaction effect of voltage, plating time on coating thickness

Fig.10, zinc coating thickness is high at high voltage and high plating time because at high voltage more quantity of zinc can be transferred to the target object and high plating time permits more deposition.

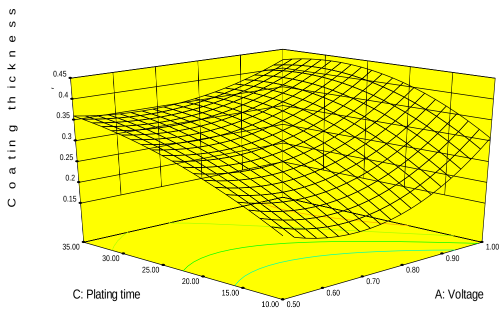

Fig.10 Interaction effect of voltage, plating time on coating thickness

F. *Interaction effect of cathode to anode distance, plating time on coating thickness*

Fig.11 depicts in studied range of cathode to anode distance, there is no significant change in coating thickness but plating time and coating thickness having direct proportion because more plating time allows more coating material to deposit on target.

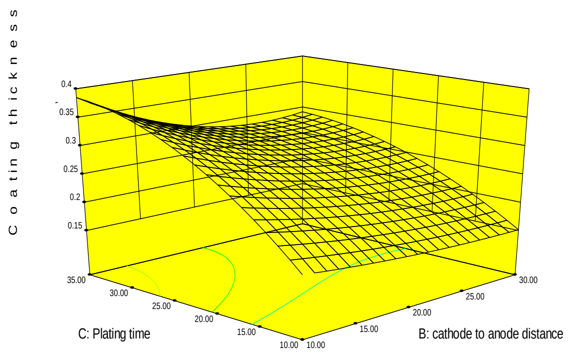

Fig.11 Interaction effect of cathode to anode distance, plating time on coating thickness

G. *Interaction effect of voltage, Cathode to anode distance on Hardness*

It is clear from Fig.12, at high voltage coating thickness are high as well as the hardness. Because high coating thickness exhibit more hardness and in low voltage thickness and hardness both are in low level.

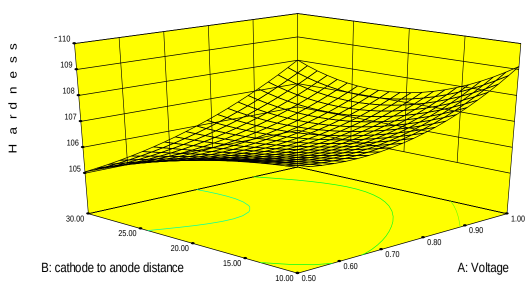

Fig. 12 Interaction effect of voltage, Cathode to anode distance on Hardness

H. *Interaction effect of voltage, plating time on Hardness*

From Fig.13 Hardness is low in low voltage as well as in less plating time; owing to the insufficient parameters level the formation of coating layer is thin so on it exhibit lower hardness.

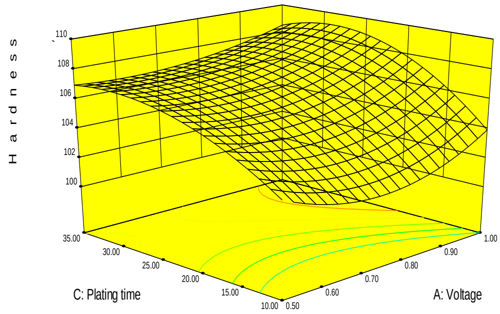

Fig.13 Interaction effect of voltage, plating time on Hardness

I. *Interaction effect of cathode to anode distance, plating time on Hardness*

Fig.14 depicts in studied range of cathode to anode distance, there is no significant change in hardness but plating time, coating thickness and hardness all are having direct proportion because more plating time allows more coating material to deposit on substrate and due to the higher thickness hardness is high.

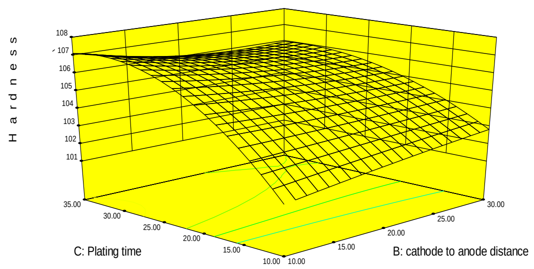

Fig.14 Interaction effect of cathode to anode distance, plating time on Hardness

IV. Conclusions

A. *Following conclusions are drawn from the analysis:*

1. Response surface methodology is a very powerful tool for designing the experiments to predict the main and interaction effects of different electroplating parameters on coating thickness and hardness.
2. Increase in voltage and plating time increases the coating thickness and hardness.

3. In studied range of electrode distance does not have any significance on responses.
4. The mathematical models developed are fully capable to predict the coating thickness and hardness in the studied parameter range.
5. Interaction effect of voltage and plating time has more influence on responses but interaction of distance between cathode to anode with other two parameters has not more influence on responses in the studied parameter range.
6. The optimum conditions of process parameters were revealed, voltage of 1.0 volts, plating time of 29.25 min and distance between the cathode to anode of 10.4 cm provides maximum coating thickness and hardness.

A. References

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