Eng. &Tech.Journal, Vol.33,Part (A), No.9, 2015

Optimization of Hot-Dip Aluminizing Process Parameters of AISI 303 Stainless Steel Using RSM

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Received on:4/3/2015 & Accepted on:30/8/2015

ABSTRACT

The coating thickness is an important factor to evaluate the coating quality and determining the properties of the hot-dip aluminizing (HDA) coating. In the present work, a hot dipping pure aluminum (99%) on stainless steel (AISI 303) rods was carried out for different diameters of rods (8, 10 and 12 mm) and different lengths (250 and 500 mm) at different aluminizing conditions of temperature and time. The dipping temperature was set to 700, 740, 780, 820 and 860℃ .The dipping time was set to 1, 2, 3, 4 and 5 minutes. A response surface methodology (RSM) using a central composite rotatable design (CCD) for a 2^3 factorial, with 5 central points and $\alpha = \pm 2$ approach, based on the experimental data, was used to obtain the optimum model to get the best thickness of coating and the best conditions of dipping. A 2^{nd} polynomial model was obtained with a confiding percentage of 95%. Analysis of the experiments using RSM indicated that 807 ℃ and 3min are optimum dipping conditions for hot-dip aluminizing process with corresponding thickness of coating layers of 134 µm to Al layer, 62.9 µm to intermetallic compound (IMC) layer and 197 µm to total coating layer.

Keywords: Aluminizing, HDA, AISI 303 Stainless Steel, RSM, Modeling and Optimization

أمثلية متغيرات عملية الألمنة بالغمر الساخن للصلب المقاوم للصدأ AISI 303 بأستخدام RSM

الخلاصة

يعتبر سمك طبقة الطلاء في طريقة الالمنة بالغمر الساخن من العوامل المهمة لتقييم نوعية الطلاء وتحديد مواصفاته. في هذا البحث تم تنفيذ عملية الالمنة بالغمر الساخن باستخدام الالمنيوم النقي بنسبة (99%) لاعمدة دائرية المقطع مصنوعة من الصلب المقاوم للصدأ (AISI 303) ذات اقطار مختلفة (8, 10 and 12 mm) واطوال مختلفة (250 and 500 mm) ولظروف ألمنة مختلفة من درجة الحرارة وزمن الغمر. تم تثبيت درجة حرارة الغمر الساخن لتكون 700, 740, 780, 820 and 860°C. اما زمن الغمر فتم تثبيته ليكون 1, 2, 3, 4 and 5 minutes . تم استخدام طريقة الاستجابة السطحية (RSM), والتي تستعمل تصميم المركز المركب (CCD) بعوامل 2^3 و5 نقاط مركزية, لانتاج موديل رياضي لحساب سمك طبقة الطلاء وكذلك تحديد الظروف المثلى لعملية

https://doi.org/10.30684/etj.2015.116232
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الالمنة وذلك بالاستناد الى النتائج العملية لقياس سمك الطلاء عند ظروف الالمنة المختلفة, حيث تم الحصول على موديل رياضي من الدرجة الثانية (a 2nd degree polynomial) بنسبة موثوقية تصل الى 95%. ان استخدام طريقة RSM لتحليل نتائج عملية الالمنة اظهر بأن ظروف الغمر المثلى هي 807°C and 3min وان ما يقابلها من سمك طبقات الطلاء هو 134.0µm لطبقة الالمنيوم (Al) , 62.9 µm للطبقة الوسطية المركبة (IMC) و 197 MM لسمك الطبقة الكلية للطلاء.

INTRODUCTION

Surface coating is an efficient and economical way to obtain the desirable material properties by altering physical, chemical, or electrical characteristics of a material. Surface modification by coatings has become an essential step to improve the surface properties such as, resistance to wear, corrosion and oxidation **[1, 2]**. Over the various techniques that have been developed to achieve surface modification, hot-dip aluminizing (HDA) of steel is one of the most effective, easiest and the least expensive techniques from a technical point of view **[3]**. The hot-dip aluminizing process was developed after 1st world war in Russia, U.S.A. and Japan. Essentially, the method consists in dipping a steel article with a clean surface into molten aluminum or its alloy and holding in it for a definite time **[4, 5, 6]**. When the steel is withdrawn from the melt, a thin film of liquid coating adheres to and subsequently solidifies on the alloy layer. The solidified film bonds the outer lustrous coating to the underlying steel substrate, and forms intermetallic compounds (IMC) of Fe_nAl_m type between the steel substrate and the melt **[4, 5, 7, 8**]. Aluminized steel due to their properties, strength and plasticity, warranted by the base material as well as corrosion and oxidation at elevated temperatures by the coating, found applications in many industrial sectors, among others in building, motorization, heat engineering, household appliances production**[4-6, 9, 10]**. For hot-dip aluminizing (HDA) process, the coating thickness is an important criterion to evaluate the coating quality and plays a key role in determining the properties of the coating **[10, 11, 12]**. In general, thicker coatings provide greater corrosion protection, whereas thinner coatings tend to give better formability and weldability **[4]**. To improve the physical properties of the intermetallic compound layer that is created during the interfacial reaction between the steel surface and molten Al, studies are underway to control the variables in the HDA process, such as the dipping time, the dipping temperature, coating thickness and the chemical composition of the molten Al **[9]**. Therefore, in order to control the hot- dip process and improve the coating quality, it is necessary to determine a mathematical relationship that can describe the correlation between hot-dip aluminizing parameters considered in this paper, i.e., coating thickness, dipping temperature, and dipping time.

This article reports our recent attempts to find a mathematical model describe the coating thickness as a function of dipping temperature and dipping time by using a response surface methodology (RSM) technique based on the experimental data of hot-dip aluminizing process of AISI 303 stainless steel rods. The experiments of hot dip aluminizing are carried out successfully by using a self-construction system of hot- dip aluminizing. The real dipping temperature, dipping time and thickness coating are measured experimentally.

Experimental Work

Materials Used

AISI 303 stainless steel as rods of circular section, Ø=8, 10, and 12 mm, with length=250 and 500 mm, was used as the substrate material (base material). The detail of the chemical composition of stainless steel is shown in **Table 1**. High purity aluminum (99%), which supplied to the crucible as ingots, was used for the dipping bath. Therefore, this HDA process is of type 2.

Specimens Preparation

The specimens were thoroughly cleaned before aluminizing. Stainless steel samples were first polished with emery papers up to 400 grade, cleaned with thinner solution and a clean cloth, and then degreased in a hot 38wt.% NaOH solution **[4]** at a temperature of 65-90 °C, rinsed with water, and then descaled in a very weak acid 0.5-1 vol% HCL solution to avoid pitting attack **[13]**, finally rinsed with water again.

Hot-Dip Aluminizing Process

A system of HDA, used in this research, is shown in **Fig. 1**. Aluminum ingots, about 15-20 ingots which equal to 150-200 Kg, were melted in graphite crucible in a resistance furnace (**Fig. 2)**, and the melt was maintained at different dipping temperatures, 700, 740, 780, 820, and 860 °C. The temperature of the molten aluminum bath was controlled to be within ±5 °C with the help of a K-type thermocouple/controller. The molten aluminum was treated with cleaning discs and powder of NH_4Cl for degassing and removing slag. The cleaning disc was pressed into melt by using a bell jar at the temperature of 700°C . The melt was stirred manually for about 10-15 min, and then dislagged thoroughly. Before every coating experiment, the temperature was carefully measured and controlled at the required level. After the chemical cleaning, the specimens were preheated to about 400 °C for about 3-5 minutes to ensure that there is no moisture on the specimen surface which effect on the coating quality and to avoid of crucible damage. Then, the specimens were immerged into the liquid aluminum for different dipping times, 1, 2, 3, 4 and 5 minutes. After the hot-dipping of the samples for the required period, the samples were taken out and quenched into a boiling water basin.

Microstructure and Layers Thickness Measurement

For microstructure observation, the aluminized specimens were properly sectioned and mounted. To observe the microstructure and measure the surface coating layers, the cross sections were mechanically polished using emery papers of grades 220–1000, and the final polishing was carried out using diamond paste. The polished specimens were etched using a solution of 50% HNO_3 and 50% HCl at room temperature. The thickness of the layers was taken as a mean value of 3 or more measurements at different places on the section. Microstructure observation was performed by optical microscopy.

Experimental design matrix

The design of experiments (DOE) is an experimental technique that helps to investigate the best combinations of process parameters, changing quantities, levels and combinations in order to obtain reliable results **[14, 15, 16, 17]**. In the present work, 2^{nd} polynomial models have been developed using RSM technique based on the experimental data of hot-dip aluminizing process of AISI 303 stainless steel rods. Situations where the curvature in the normal operating ranges is inadequately modeled by the first-order function often occur. Thus, the quadratic response surface functions should be considered. There are several choices for second-order designs. One of the most popular is the central composite design (CCD). A CCD is composed of factorial. Factorial points are the points from a 2^q design with levels coded as ± 1; center points are m points at the origin. The axial points have one design variable at $\pm\alpha$ and all other design variables at 0; there are $2q$ axial points. One of the reasons that CCD's are so popular is that can be started with a first-order design using a 2^q factorial and then augment it with axial points and perhaps more center points to get a second-order design. If the precision of the estimated response surface at some point x depends only on the distance from x to the origin, not on the direction, then the design is said to be rotatable. Thus rotatable designs do not for rotatable favor one direction over another when we explore the surface [15, 17].

A response surface methodology (RSM) using a central composite rotatable design (CCD) for a 2^3 factorial, with 5 central points and $\alpha = \pm 2$ approach was undertaken. A total of 13 experiments (runs) were performed according to the experimental design matrix .The runs were performed at random using the run order listed in **Table 3**. Each parameter was used at different code levels of −2, −1, 0, +1, and +2, whereby each level used conformed to an actual value equivalent to the coded value. Thus, the input parameters studied are thickness of layer, dipping temperature and dipping time. The experimental design matrix used for input parameters in terms of actual factors with the experimental measured values of HDA process is given in **Table 2**. The software DESIGN EXPERT version 8 was used to develop the model. This software is normally used to design the matrix for the experiments required to conduct the experimental test in this paper work. It normally includes the response surface methodology (RSM) technique that used to perform the necessary statistical steps for model adequacy and build the empirical equation (mathematical model) in terms of input and output parameters, additionally RSM also provides the optimization facility for obtaining the optimum input and the output conditions. The prediction models are within a 95% confidence interval.

Results and Discussion

Figure 3 shows the photographs of some results of HDA process illustrating the aluminized and non-aluminized specimens in the present research. One can see that the process of HDA was successfully carried out and the coating surface was smooth and regular. Microstructure of hot-dip aluminized sample of AISI 303 stainless steel, for dipping temperature of 740 ℃ and dipping time of 5 min, is shown in **Fig. 4**. Three distinct regions which could be easily identified in these microstructures include: the outer aluminum layer, the intermetallic compound layer (IMC), and the substrate stainless steel. A typical feature of aluminizing in pure aluminum (in the temperature range of 700-860ºC and for different dipping times) was the even interface between the intermetallic compound layer and the substrate stainless steel.

Modeling the Coating Layers Thickness

The selection of appropriate model and the development of response surface models have been carried out by using statistical software. The regression equations for the selected model were obtained for the response characteristics. These regression equations were developed using the experimental data (**Table 3**) and were plotted to investigate the effect of process variables on various response characteristics.

The analysis of variance (ANOVA) was performed to statistically analyze the results. Analysis of variance (ANOVA) method has been applied to find out the significance of main factors and interaction factor. ANOVA is performed to see statistically significant process parameters and percent contribution of these parameters on the characteristic properties. Larger F-value indicates that the variation of the process parameter make a big change on the performance characteristics **[14, 15, 16, 18]**. **Table 4** depicts the suggested models for responses and minimum and maximum ranges of responses and parameters.

The Model F-value of 5-9 in **Table 3** implies the model is significant. The Values of ‘Prob> F’ less than 0.0500 indicate model terms are significant. In this case A, B, and C are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. So to improve the model the insignificant terms from **Tables 4, 5 and 6** were eliminated.

Response Surface Model

Response surface methodology (RSM), based on the experimental data of HDA process of AISI 303 stainless steel, carried in the present research , was used to obtain a Quadratic model to describe the thickness of coating as a function of dipping temperature (T) in °C and dipping time (t) in minutes. The obtained model was with a confiding percentage of 95%, and is given below.

Aluminum layer thickness

The final equation in terms of coded factors:

$$\textbf{Al layer thickness} = +106.44 + 30.49 * A + 20.01 * B - 11.52 * A * B + 10.03 * A^2 - 13.49B^2 \quad \dots (1)$$

The final equation in terms of actual factors:

$$\textbf{Al layer thickness} = +2468.62110 - 8.14827 * T + 325.563 * t - 0.288 * T * t + 6.26575E - 003 * T^2 - 13.48606 * t^2 \quad \dots.(2)$$

1.Intermediate layer (IM) thickness

The final equation in terms of coded factors:

$$\textbf{Intermediate layer thickness} = \mathbf{+68.70 - 3.90 * A + 10.26 * B - 1.51 * A * B - 13.11 * A^2 - 8.67 * B^2} \quad \dots\dots\dots (3)$$

The final equation in terms of actual factors:

Intermediate thickness =

$$-5038.41126 + 12.79999 * T + 91.82996 * t - 0.037875 * T * t - 8.19479E - 003 * T^2 - 8.67041 * t^2 \quad \ldots\ldots (4)$$

Total layer thickness

The final equation in terms of coded factors:

Total coated layer thickness $= +175.15 + 26.59 * A + 30.26 * B - 13.02 * A * B - 3.09 * A^2 - 22.16 * B \quad \ldots\ldots\ldots (5)$

The final equation in terms of actual factors:

Total coating thickness $= -2568.33041 + 4.64972 * T + 416.99422 * t - 0.32537 * T * t - 1.92883E - 003 * T^2 - 22.15612 * t^2 \quad \ldots\ldots\ldots (6)$

The diagnostic checking of the models has been carried out using residual analysis and the results are presented in **Figures 5, 6 and 7** show the standardized residuals with respect to the predicted values. The figures revealed that the residuals fall on a straight line implying that the errors are distributed normally. The residuals do not show any obvious pattern and are this implies that the models are adequate and there is no reason to suspect any violation of the independence or constant variance assumption. **Figures from 8 to 13** respectively represent 2D and 3D contour graph of Al, IMC and total layer thickness as a function of time and temperature, one can see that Al layer thickness is increased with increased in both dipping temperature and dipping time, the IMC layer thickness is decreased with increased in dipping temperature and increased with increased in dipping time, but the degree of increasing of IMC layer thickness with dipping time is relatively greater than decreasing of IMC layer thickness with dipping temperature, the total coated layer thickness is increased with increased dipping temperature and dipping time, but the influence of dipping temperature was greater than dipping time. To make a comparison between the predicated and actual values of Al, IMC and total coated layer thickness, **Figures 14, 15 and 16** were constructed. One can see there is a good correlation between the predicated and actual values of Al, IMC and total coating layer thickness with range of 15-210 µm, 8.3-71.65 µm and 28-218.30 µm respectively.

Numerical Optimization

For the hot-dip Aluminizing of AISI 303 stainless steel, the optimum conditions are required to achieve the best coating thickness within predetermined parameters. **Table 7** gives a design summery for main factors and response with a “Quadratic” design model and **Table 8** is represent the numerical optimization of the responses for each variable. The optimal values of HDA process parameters are: dipping temperature of 807 °C and dipping time of 3.0 min, **Table 9**. At these aluminizing conditions, a maximum layers thickness was as follow: Al layer thickness of 134 μm (**Fig. 24**), IMC layer thickness of 62.9 μm (**Fig. 25**) and total coating layer thickness of 197 μm (**Fig. 26**).

CONCLUSIONS

A series of experiments using RSM were conducted to investigate the factors affecting the HDA process of AISI 303 stainless steel rods. The effect of dipping temperature, dipping time and thickness of coating layers was studied. Based on this study, the following conclusions can be arrived at:

1. Quadratic equations were obtained by using RSM technique for the three thickness responses at different temperatures and times.
2. This work demonstrated that the HDA process was successfully performed with a good quality of the resultant coating having a smooth, homogenous texture and desirable thickness of Al layer reaching to 210 μm.
3. This study shows that Al layer thickness is increased with increasing in dipping temperature and dipping time. There is a good correlation between the predicted and actual values of Al layer thickness with a range of 15-210 µm. The influence of dipping time on the Al layer thickness is greater than the influence of dipping temperature; Whereas, IMC thickness is decreased with dipping temperature and increased with dipping time.
4. The IMC layer thickness is decreased with increased dipping temperature and increased with increased dipping time, but the degree of increasing of IMC layer thickness with dipping time is relatively greater than decreasing of IMC layer thickness with dipping temperature.
5. The total coated layer thickness is increased with increased dipping temperature and dipping time, but the influence of dipping temperature is greater than dipping time.
6. The best coating thickness was achieved when optimal conditions of the HDA are: dipping temperature of 807℃, dipping time at 3.0 min and the thickness of Al layer, IMC layer and total layer are 134 μm, 62.9 μm and 197 μm , respectively.
7. RSM technique as a tool was found useful to be used for obtaining the optimum thickness for any given input set in aluminization process.
8.

Table (1): Chemical compositions (wt. %) of the used and standard AISI 303 stainless steel

Alloy	C	Si	Mn	P	Cr	Ni
Used material [a]	0.114	0.539	1.14	0.032	18.20	8.19
Standard (ASM) [4]	Up to 0.15	Up to 1.0	Up to 2.0	Up to 0.2	17-19	8-10

a : Source: State Company for Inspection and Engineering Rehabilitation (SIER)/Baghdad.Laboratory and Engineering Inspection Department Minerals Lab. (Spectral analysis of metals) stainless steel rod sampl*e*

Table (2): Levels of input parameters

Input factor	Unit	Low Level	High Level	- alpha	+ alpha
Temperature	˚C	740	820	700	860
Time	min	2	4	1	5

Table (3): Design matrix for actual input factors and responses values

Std.	Run No.	Temperature (˚C)	Time (min)	Al layer thickness (μm)	IMC layer thickness (μm)	Total thickness (μm)
1	13	740	2	40.92	38.81	79.81
2	8	820	2	120.00	34.92	154.92
3	4	740	4	109.00	60.82	169.82
4	10	820	4	142.00	50.87	192.87
5	3	700	3	83.09	24.78	107.87
6	11	860	3	210.00	8.30	218.30
7	12	780	1	115.00	13.00	28.00
8	6	780	5	90.00	55.61	145.61
9	2	780	3	110.00	71.65	181.65
10	7	780	3	115.00	65.75	180.75
11	1	780	3	95.00	65.75	160.75
12	9	780	3	100.20	70.85	171.05
13	5	780	3	112.02	70.65	182.67

Table (4): ANOVA analysis for Response Surface Reduced Quadratic Model (Al layer thickness)

Source	Sum of squares	df	Mean square	F value	p-value Prob > F
Model	25442.28	5	5088.46	98.55	< 0.0001 significant
A-Temperature	11156.90	1	11156.90	216.07	< 0.0001
B-Time	4803.20	1	4803.20	93.02	< 0.0001
AB	530.84	1	530.84	10.28	0.0149
A^2	2302.92	1	2302.9	44.60	0.0003
B^2	4167.38	1	4167.38	80.71	< 0.0001
Residual	361.45	7	51.64		
Lack of Fit	74.56	3	24.85	0.35	0.7948 not significant
Pure Error	286.89	4	71.72		
Cor Total	25803.73	12			

Std. Dev.	7.19	R-Squared	0.9860
Mean	13.25	Adj R-Squared	0.9760
C.V.%	6.96	Pred R-Squared	0.9543
Press	1177.98	Adeq Precision	3.953

Table (5): ANOVA analysis for Response Surface Reduced Quadratic Model (Intermediate layer (IMC) thickness)

Source	Sum of squares	df	Mean square	F value	p-value Prob > F
Model	6005.37	5	1201.07	205.59	< 0.0001 significant
A-Temperature	182.52	1	182.52	31.24	< 0.0008
B-Time	1264.44	1	1264.44	216.44	< 0.0001
AB	9.18	1	9.18	1.57	0.2502
A^2	3939.20	1	3939.20	674.29	0.0001
B^2	1722.55	1	1722.55	294.86	< 0.0001
Residual	40.89	7	5.84		
Lack of Fit	6.63	3	2.21	0.26	0.8528 not significant
Pure Error	34.27	4	8.57		
Cor Total	6046.26	12			

Std. Dev.	2.42	R-Squared	0.9932
Mean	48.60	Adj R-Squared	0.9884
C.V.%	4.97	Pred R-Squared	0.9816
Press	111.23	Adeq Precision	36.960

Table (6): ANOVA analysis for Response Surface Reduced Quadratic Model (Total coated layer thickness)

Source	Sum of squares	df	Mean square	F value	p-value Prob > F
Model	31654.51	5	6330.90	111.12	< 0.0001 significant
A-Temperature	8481.15	1	8481.15	148.86	< 0.0001
B-Time	10991.64	1	10991.64	192.93	< 0.0001
AB	677.56	1	677.56	11.89	0.0107
A^2	218.23	1	218.23	3.83	0.0912
B^2	11248.13	1	11248.13	197.43	< 0.0001
Residual	398.81	7	56.97		
Lack of Fit	44.73	3	14.91	0.17	0.9124 not significant
Pure Error	354.08	4	88.52		
Cor Total	32053.32	12			

Std. Dev.	7.55	R-Squared	0.9876
Mean	151.85	Adj R-Squared	0.9787
C.V. %	4.97	Pred R-Squared	0.9699
PRESS	966.41	Adeq Precision	37.048

Table (7): Design summery for main factors and response (Design model: Quadratic)

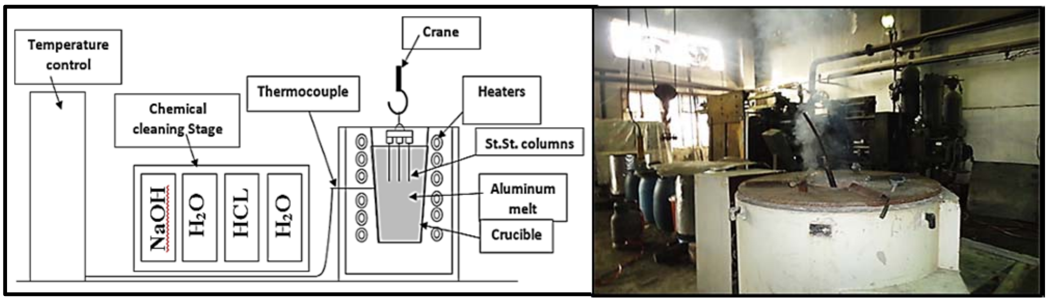
Factor	**Name**	**Unit**	**Min.**	**Max.**	**Coded value**	**Mean**	**Std. Dev.**
A	Temperature	C °	70	860	-1.000= 740 1.000 = 840	780	38
B	Time	min	1	5	-1.000=2 1.000= 4	3	1
Response	**Name**	**Unit**	**Min.**	**Max.**	**Mean**	**Ratio.**	**Std. Dev.**
Y1	Al layer thickness	µm	5.00	210.00	103.248	14	46.3714
Y2	Intermediate layer thickness	µm	8.30	71.65	48.5969	8.63253	22.4467
Y3	Total coated layer thickness	µm	28.00	218.30	151.852	7.79643	51.6828

Table(8): Constrains of each variable for numerical optimization of the responses

Types of variables	**Goal**	**Lower Limit**	**Upper Limit**	**Lower Weight**	**Upper Weight**	**Importance**
A:Temperature	is in range	740	820	1	1	3
B:Time	is in range	2	4	1	1	3
Al layer thickness	maximize	15	210	1	1	3
Intermediate layer thickness	maximize	8.3	71.65	1	1	3
Total coated layer thickness	maximize	28	218.3	1	1	3

Table (9): Optimal conditions used to obtain the maximum layers thickness.

No.	**Temperature** (˚C)	**Time** (min)	**Al layer thickness** (**µ**m)	**Intermediate layer thickness** (**µ**m)	**Total coated layer thickness** (**µ**m)	**Desirability**
1	807	3	134.60	62.39	197.00	0.775 Selected



Figure(1): Schematic diagram and photograph of the HDA system used in the present research.

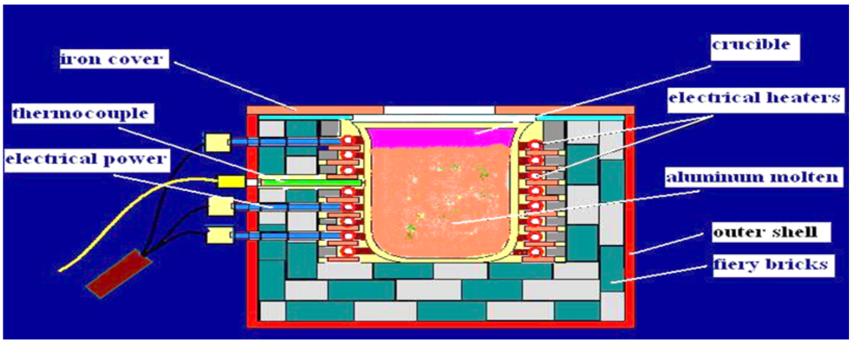
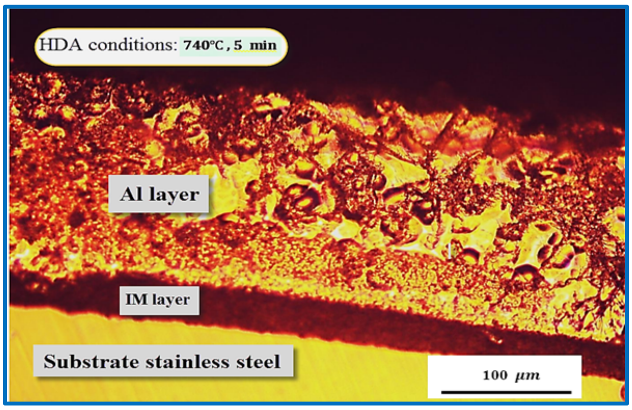


Figure (2): Melting furnace used in the present research.

specimens	Before HDA	After HDA
Ø8mm L=250,and 500 mm		
Ø10mm L=250mm		
Ø12mm L=250mm		
Tensile sps. Do≅6mm L=250, 220 mm		

Figure(3): Photographs of some result of HDA process illustrating the aluminized and non-aluminized specimens.



Figure(4): Three distinct regions in microstructures of a HDA sample at dipping conditions of 740 °C and 5 min: the outer pure aluminum layer (Al-layer), the intermetallic layer (IM) and the substrate stainless steel.

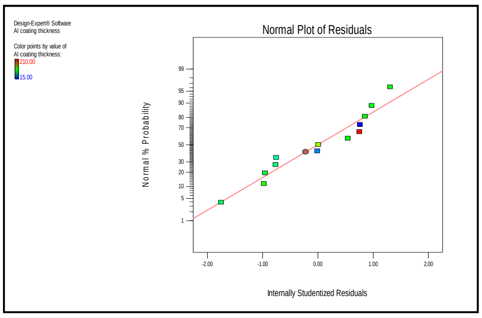
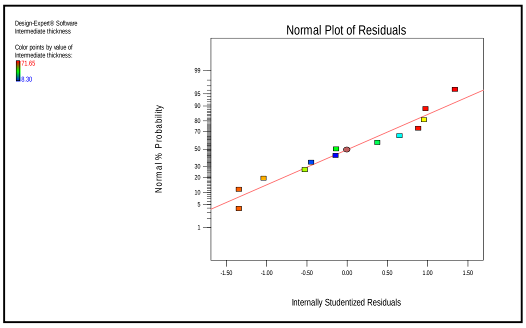
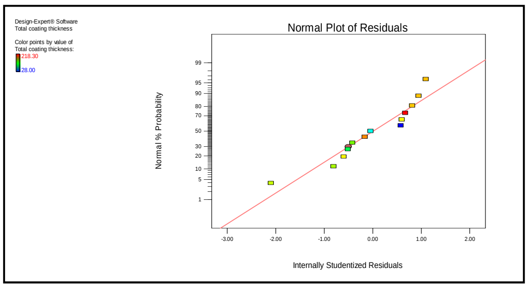


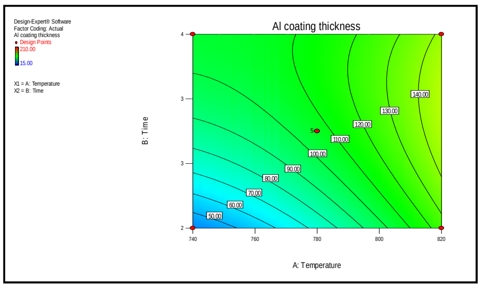
Figure (5): Normal probability plot for Al layer thickness



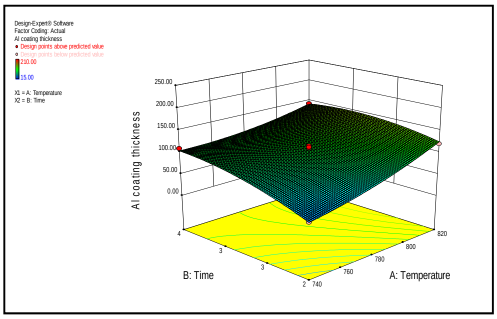
Figure(6): Normal probability plot for intermediate layer thickness



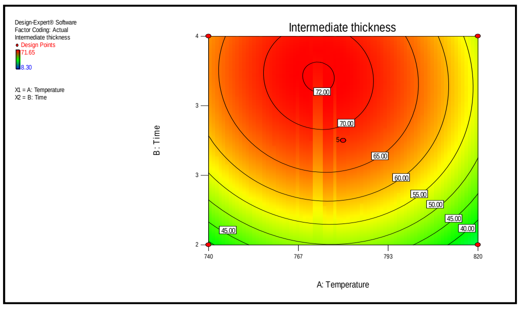
Figure(7): Normal probability plot for total coated layer thickness



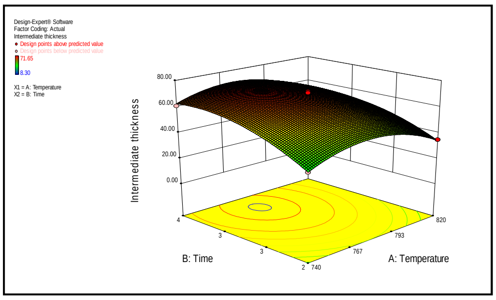
Figure(8): 2D contour graph of Al layer thickness as a function of time and temperature



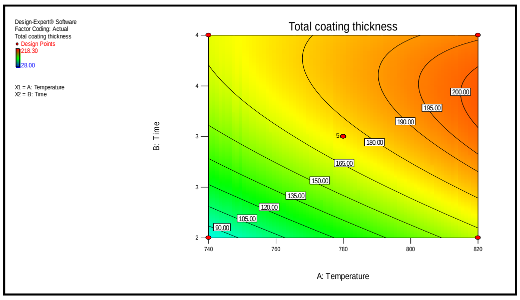
Figure(9): 3D Graph of Al layer thickness as a function time and temperature



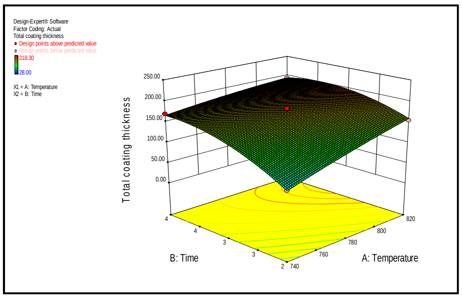
Figure(10): 2D contour graph of intermediate layer thickness as a function of time and temperature



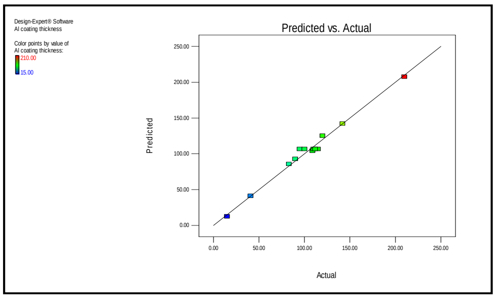
Figure(11): 3D Graph of intermediate layer thickness as a function time and temperature



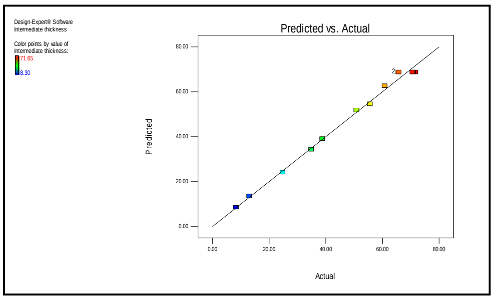
Figure(12): 2D contour graph of total coated layer thickness as a function of time and temperature



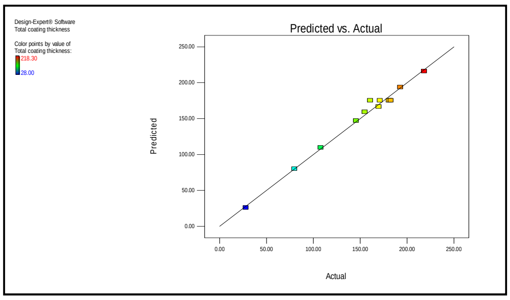
Figure(13): 3D Graph of total coated layer thickness as a function time and temperature



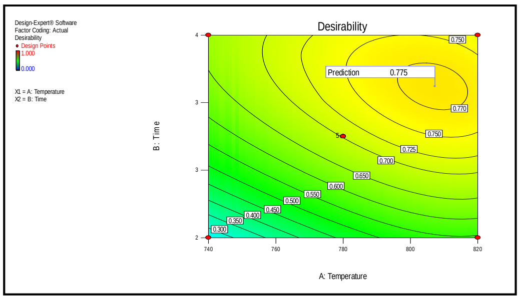
Figure(14): Predicted versus Al layer thickness actual data for comparison



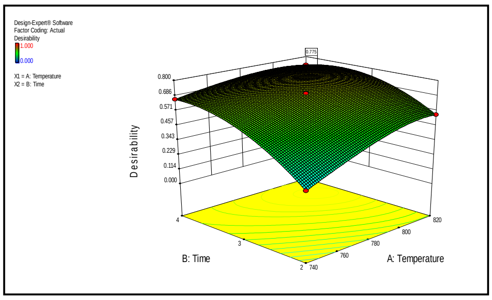
Figure(1)5: Predicted versus intermediate layer thickness actual data for comparison



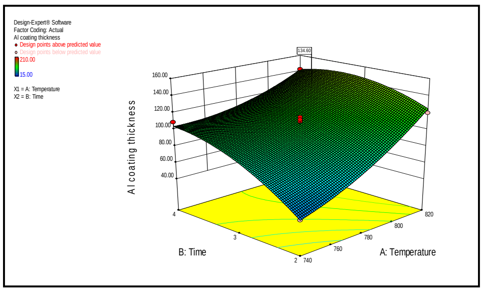
Figure(16): Predicted versus total coated layer thickness actual data for comparison



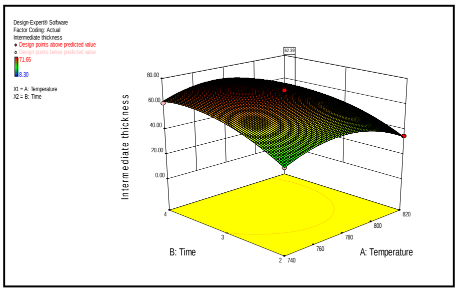
Figure(17): 2D Contour for desirability as a function of time and temperature



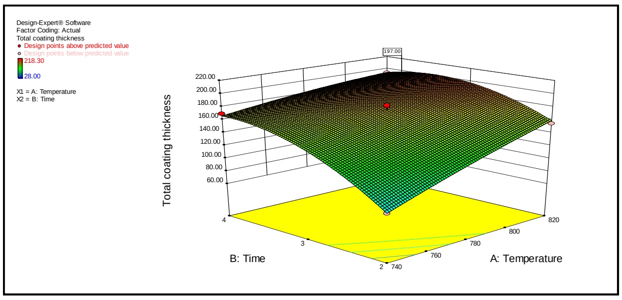
Figure(18): 3D Surface plot for desirability as a function time and temperature



Figure(19): 3D surface plot showing the optimum value of maximum Al layer thickness obtained



Figure(20): 3D surface plot showing the optimum value of maximum Intermediate layer thickness obtained



Figure(21): 3D surface plot showing the optimum value of maximum of total layer thickness obtained

REFERENCES

[1]. Sung-Ha Hwang, Jin-Hwa Song, and Yong-Suk Kim, "Effects of carbon content of carbon steel on its dissolution into a molten aluminum alloy", Materials Science and Engineering A 390, pp. 437–443, 2005.

[2]. Hishamuddin Hj. Husain, Muhamad Daud, Anasyida Abu Seman and Abdul Razak Daud, "Preliminary Study on Metallic Coating of Steel Substrates through Hot Dip Aluminizing by Using Energy Dispersive X-Ray Spectroscopy (EDX) Technique", Journal of Nuclear and Related Technologies, Vol. 6, No. 2,pp. 63-69, December, 2009.

[3]. Mohammad Emami, Hamid Reza Shahverdi, Shigenari Hayashi, and Mohammad Javad Torkamany, "A Combined Hot Dip Aluminizing/Laser Alloying Treatment to Produce Iron-Rich Aluminides on Alloy Steel", Metallurgical and Materials Transactions A, 23 February, 2013.

[4]. ASM Handbook,"Surface Engineering", ASM International, Vol. 5, 1994.

[5]. V. R. Ryabov, "Aluminizing of Steel", Oxonian Press, New Delhi, 1985.

[6]. Gul Hameed Awan, "The Morphology of Coating-Substrate Interface in Hot - Dip-Aluminized Steels". Ph.D. Thesis, Department of Metallurgical and Materials Engineering, University of Engineering and Technology, Lahore-Pakistan, 2001.

[7]. G. H. Awan, F. Ahmed, L. Ali, M. S. Shuja and F. Hasan, "Effect of Coating thickness on the Formability of Hot Dip Aluminized Steel", Pak. J. Engg. & Appl. Sci. Vol. 2, Jan 2008.

[8]. Kee-Hyun Kim, Van-Daele Benny, Van-Tendeloo Gustaaf and Jong-Kyu Yoon, "Observations of Intermetallic Compound Formation of Hot Dip Aluminized Steel", Materials Science Forum Vols. 519-521, pp. 1871-1875, 2006.

[9]. Sungmin Kang, Kwangsik Han, Kwangwon Kim, Yongju Kang, Kwangsuk Son and Donggyu Kim, "Formation Behavior of an Intermetallic Compound Layer during the Hot Dip Aluminizing of Cast Iron", ISIJ International, Vol. 52, No. 7, pp. 1342–1347, 2012.

[10]. K. ŻABA, “The Influence of Temperature and Time of Exhibition on Change of Al-Si Coating Thickness and Surface Texture on the Steel Plates”, Archives of Metallurgy and Materials, Vol. 55, p.p. 151-162, 2010.
[11]. Xiao Gang, Shangguan Qi, Lu Y. Uheng, Huang Caim in and Zeng Jianmin, “Heat Transfer during the Solidification of Hot Dip Aluminizing Coating”, Chinese Journal of Mechanical Engineering, Vol. 24, No.3, pp. 1-6, 2011.
[12]. K. ŻABA, “Influence of Heat Treatment on the Al-Si Coating Adhesion to Steel Strips”, Archives of Foundry Engineering, Vol. 10, pp. 17-22, 2010.
[13]. American Iron and Steel Institute (AISI),”Cleaning and Descaling Stainless Steels”, A designer’s handbook series, No. 9001, 1982.
[14]. D. C. Montgomery, “Design and Analysis of Experiments”, 5th Edition, John Wiley & Sons Inc., 2001.
[15]. D. C. Montgomery, “Design and Analysis of Experiments: Response Surface Method and Designs”, New Jersey: John Wiley and Sons, Inc., 2005.
[16]. Abbas Khammas Hussein, “Optimization of Cyclic Oxidation Parameters in Steel-T21 for Aluminization Coating Using Taguchi-ANOVA analysis by MINITAB13”, Eng. & Tech. Journal, Vol. 27, No. 12, pp. 2367-2384, 2009.
[17]. Gary W. Oehlert, “A First Course in Design and Analysis of Experiments”, Library of Congress Cataloging-in-Publication Data, 2010.
[18]. Mouhamed M. Hamadi, Amjad B. Abdulghafour and Haider. N. Ugla,” Optimizing Coating Process Parameters by Using Taguchi Experimental Design to Increasing Wear Resistance of Steel CK50”, Eng. & Tech. Journal, Vol. 32, part (A), No. 12, pp. 2862-2873, 2014.