

## Study on Influence Factors of zinc layer thickness via Response Surface Method, Taguchi Method and Genetic Algorithm

Yi Wang\*

Hong Kong University of Science and Technology, Kowloon, Hong Kong

### Abstract

Air knife is the key equipment to determine zinc coating thickness in the hot-dip galvanizing process. The process parameters related to air knife directly determine whether the desired coating thickness can be obtained. Therefore, setting the optimal process parameters is the key step to improve hot dip galvanizing process capability and zinc coating quality. Previous research on zinc layer thickness was based on the principle of physics and simulation to build models and few studies were carried about the interaction between parameters of air knife. In this research, three process parameters (stripe velocity, air pressure and air knife-stripe distance) were considered to optimize coating thickness by Response Surface Method (RSM), Taguchi method and Genetic Algorithm (GA). This paper firstly used response surface method (RSM) to establish polynomial model and discuss interaction effect between air pressure and the range of air knife. Then, this paper used Taguchi method to do the robustness analysis of air knife and validate the polynomial model from response surface method. Finally, this paper built suitable a fitness function and then uses genetic algorithm to find the optimal combination of parameters for a given thickness of zinc layer. This proposed integrated method is a good try to combine RSM, Taguchi method and GA.

**Keywords:** Air knife; Hot-dip galvanizing process; Coating thickness; Response surface method; Taguchi method; Genetic Algorithm (GA)

### Introduction

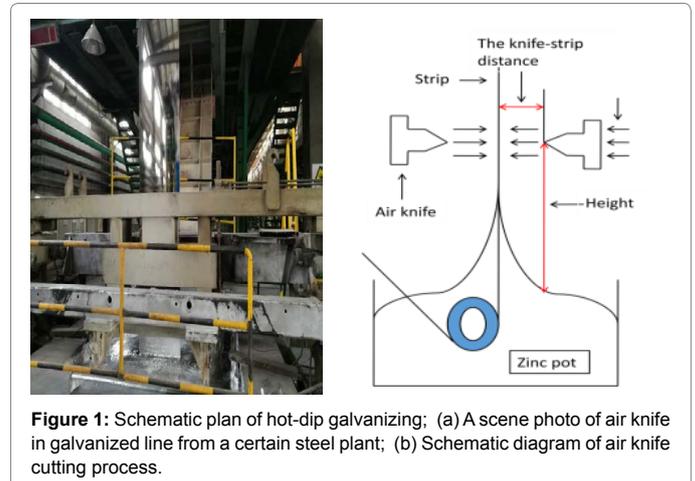
The optimization of process parameters is routinely performed in the manufacturing industry so as to solve the challenges in product quality and/or optimize the cost effectiveness of manufacturing processes [1]. Hot dip coating thickness control technology has experienced from the hand dip plating method to roll coating method to the development process of blowing method. In hot-dip galvanizing process, zinc coating thickness is one of the main quality control factors of galvanized steel strip. Whether zinc coating thickness is in line with the needs of customers has critically important effects on the price of galvanized sheet. So zinc coating thickness control is not only an industrial problem, but also an economic concern in modern rolling mills.

Zinc coating thickness control includes two aspects: (1) Quality index, the uniformity of strip surface; (2) Cost index, mainly considering the deviation between the target thickness and the actual thickness [2,3]. Therefore, whether the zinc thickness reaches the customers' standard or not is the key to decide the product quality. On the process of hot-dip galvanizing, air knife is the key equipment to control the coating thickness [4]. The working principle of air knife is shown in Figure 1. As shown in Figure 1, under the protection of the protective gas, the strip is annealed in the furnace and then dipped into the zinc bath. After strip is pulled out from zinc pot, the impact of the high velocity airflow from air knife will adhere to the strip surface and make the excess zinc liquid blown back to the zinc pot.

According to previous research on air knife, zinc coating thickness can be obviously influenced by the values of process parameters related including: air pressure, the range of air knife, the height of air knife, knife-lip gap and the angle of air knife. Early in 1976, Thornton and Graff [4] deduced the calculation model of the zinc coating thickness, considering only the effect of air knife pressure. Then, based on the research of Ellen and Tu [5] considered the effect of flow shear stress to coating thickness. Delphine et al. [6] simulated the flow of air flow and considered the flow of liquid and gas at the same time. Aha and Chung [7] focused on the study of the flow field in the edge of the

strip and discussed the reason of excessive zinc in the strip. Gosset and Buchlin [8] analyzed the effect of gas nozzle shape on gas flow field and discussed the splash behavior.

Except for single physical models, the numerical simulation technique has been applied to the parameter optimization of air knife. Zhang et al. [9] established four first-order polynomial multi-parameter models to predict different targeted coating thicknesses by numerical simulation as FLUENT and discussed the influences of the outlet pressure, the nozzle to strip distance, the slot opening, the edge baffle



**Figure 1:** Schematic plan of hot-dip galvanizing; (a) A scene photo of air knife in galvanized line from a certain steel plant; (b) Schematic diagram of air knife cutting process.

\*Corresponding author: Yi Wang, Hong Kong University of Science and Technology, Kowloon, Hong Kong, Tel: +85234692430; E-mail: [wangyiluckyforever@163.com](mailto:wangyiluckyforever@163.com)

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plate as well as the tilting angle of air knife. Lacanette et al. [10] analyzed the effect of the gas-jet nozzle to substrate standoff distance on the final coating thickness through numerical simulations and investigated the occurrence of the splashing phenomenon. Elsaadawy et al. [11] developed a coating weight model to describe the pressure and wall shear stress distributions for the prediction of coating weight. Shin et al. develop a synthesis method including a long term model and a short term model to analyze the nonlinear coating weight control problem as a linear control problem [12]. Kweon and Kim [13] discussed the effect of the height of nozzle slot in the air knife wiping process in detail based on the results from a finite volume method (FVM).

In summary, most existing studies are based on the principle of physics and simulation to build optimization models. Those types of models are more precise but not very reliable and sufficient. Three reasons could account for that. The first reason is that these models are critically difficult for common workers to understand, which may negatively influence the efficiency of practical applications. For example, air knife height, air knife angle and knife-lip clearance are fixed or stable in a very small range because of the difficulty to adjust and control them, so actually it is not significant to put these parameters into a mathematical model. The second reason is that most research on air knife ignored the interaction between different parameters of air knife. Actually, when there is interaction between two different factors, it is meaningless to simply study the effect of one factor, and the role of this factor must be studied at different levels of another factor. So it's not realistic to consider the optimal levels of each factor individually. The third reason is that few research considered the potential influence of the parameters' fluctuation on the system performance. Actually, it's necessary to consider the fluctuation of parameters in the process of setting optimal values of parameters because the stability of air knife also has an affect on product quality. To solve those problems above, this paper choose three most important parameters of air knife to build a more practical polynomial model according to response surface method and discussed the interaction between strip speed and air knife range. Then, this paper used Taguchi method to discuss the stability of the system and eventually found the position factor and divergence factor. Finally, according to the conclusions of experiments above, this paper built a suitable fitness function and used GA to find the optimal parameter combination. This integrated method should be considered as a good try to combine RSM, Taguchi method and genetic algorithm. The structure of this paper can be listed as follows. Methodologies will introduce the principle of Response Surface Method, Taguchi Experimental Design and GA. The proposed integrated approach will describe the designs of CCD experiment, Taguchi experiment and GA. 4 Results and discussions will show the results and discussions of experiments, followed by a brief conclusion in Conclusion.

## Methodologies

### Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is often used in the complex optimization calculation process, which is a method based on orthogonal experimental theory. In practical work, researchers often need to study how the dependent variable Y depends on independent variables, and then find the optimal setting of independent variables so that the response variable gets the best value ('looking big', 'looking small' or 'looking at the target'). Through the experimental data, RSM helps researchers establish the equation between independent variables and dependent variables, and then to predict the best output value

[14,15]. The output value is obtained based on the regression analysis of control values of independent variables. In 1951, Box and Wilson [16] introduced response surface methodology for the first time. Compared with the previous full factorial experimental design, the number of experiments was greatly reduced. In addition, the experimental results obtained by response surface methodology are also considered to be statistically acceptable [17]. Besides, the Response Surface Method is one of the best methods to deal with these types of problems if the number of independent variables is less than three. Besides, RSM is especially suitable for the case of "looking big" or "looking small" and the robust design method (Taguchi method) is more suitable for the case of 'looking at the target'. The implementation steps of RSM are listed as follows: (1) Experimental design; (2) Statistical analysis and build regression model; (3) Variable optimization through model equation. Central composite design (CCD) and Box Behnken design are the most commonly used experimental design methods. The greatest advantages of these types of experimental designs are the reduction in the number of experiments and the good prediction for dependent variables [18]. For example, on the premise of four independent variables, total factor analysis require at least 81 rounds of experimental [16], while the CCD method requires only 31 rounds of experiments (16 cube points, 8 star points and 6 central points).

### Taguchi method

Taguchi method was invented and developed by Dr. Genichi Taguchi, a Japanese quality control expert, in the 1950s [19], which is widely used to the optimization of process parameters especially in the field of manufacturing, which has proven to be highly effective [20]. This method only needs small number of experiments to study the entire parameter space by a special design of orthogonal arrays [21]. For the purpose of robust design and best product quality, three types of design methods have been entailed: system design, parameter design and tolerance design [22]. Parameter design is the core of three kinds of design where the optimum value and optimum combination of each element parameter affecting the system quality characteristics are selected by orthogonal experimental design. The purpose of system design is to determine the suitable working levels of design factors [23]. Steps of Taguchi method include: (1) Making controllable factor level table; (2) Making control table; (3) Making error factor level table; (4) Making noise table; (5) Experiment; (6) Analyze outcomes by signal to noise ratio (S/N), principal effect diagram and ANOVA. The Taguchi method is not only to promote full use of inexpensive components to design and produce high quality products, but advanced test technology can be used to reduce the design cost of test. The difference between the Taguchi method and other experimental methods are: other experimental methods generally rely on the repeated experiments performed to estimate the error, after all, the ultimate target is the response variable itself, while robust parameter design takes variation as the final research object, the purpose is to find and identify variables that can directly affect the performance deterioration, which essentially extends the function and the requirements [24,25].

### Genetic algorithm

Genetic Algorithm is a method of searching the optimal solution by simulating the natural evolution process, which is a computational model simulating the natural selection process of Darwin's theory of biological evolution [26]. In technology and science, GAs has been used adaptive algorithms for solving practical problems and as computational models of natural evolutionary systems [27]. By using the probabilistic optimization method, the genetic algorithm can

automatically obtain and guide the search space, adjust the search direction adaptively, and do not need to determine the rules. It has been successfully used in job-shop scheduling, production planning, line balancing, lumber cutting optimization, and process optimization [28]. Goldberg has suggested a most common and useful form of GA [29]. The basic steps of the genetic algorithm are listed as follows:

1. Chromosome encoding, determine the length and the population size of chromosome; crossover probability and mutation probability;
2. Define the fitness function to evaluate the fitness;
3. Randomly generated initial chromosome;
4. Calculate the fitness function of chromosomes;
5. Choose a pair of chromosomes for mating. Chromosomes with high fitness have higher probability to be chosen. Roulette method is commonly used in the selection of chromosome [30];
6. Generate offspring chromosomes through crossover and mutation;
7. Repeat step 5, until it reaches the specified genetic algebra;
8. Replace the initial chromosome with the new generation;
9. Repeat step 4-8 until it reaches the standard of fitness function.

### Steps for process parameter optimization

A flow chart diagram is presented in Figure 2 to show the concrete steps. In the parameter optimization, air pressure, the knife-strip distance and strip velocity were entered as the explanatory variables, and the coating thickness was the response variable.

Step 1: Design experiments according RSM, and manufacture according the experiment design.

Step 2: Build regression model and analysis of variance (ANOVA).

Step 3: Use response surface analysis to analyze interactions.

Step 4: Build regression model and analysis of variance (ANOVA).

Step 5: Design experiments according Taguchi method, and manufacture according the experiment design.

Step 6: Analyze the system robustness and verify conclusions from RSM.

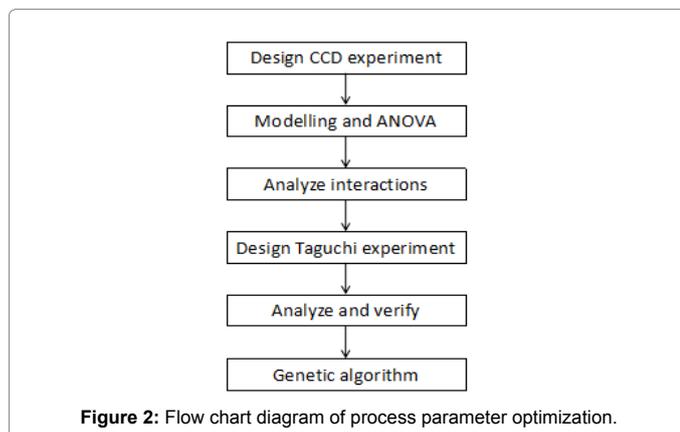


Figure 2: Flow chart diagram of process parameter optimization.

Step 7: Create a suitable fitness functions and solve optimal solutions by genetic algorithm.

## The Proposed Integrated Approach

### Design of CCD experiment

This research proposes the RSM to optimize the air-knife cutting process, and efficiently determine the interactions between Zinc coating thickness and three main process parameters (air pressure, the range of air knife and strip velocity). Moreover, the interaction between strip velocity and the range of air knife has been fully discussed.

The strip specification used in the experiment is  $1.5 \times 860$  (cm). The preheated strip comes from the annealing furnace and zinc bath that is heated at  $460^\circ\text{C}$  (0.0077% of Iron content and 0.4% of aluminum content). Air-knife height is fixed in 220 mm. Air-knife angle is maintained at  $90^\circ$ . Knife-lip clearance is steady between 0.6 mm and 0.8 mm. The criteria of other process parameters are illustrated in Table 1. As for three main process variables, the air pressure (MPa) is controlled by a frequency conversion motor knob, which can be controlled by workers. The range of air knife (cm) can be adjusted by a hand-type motor and the stripe velocity (m/min) could be hold by the central control system.

Zinc coating thickness is accurately measured by weight-reducing method. Firstly, measure the samples by electronic scale and then wash away the zinc coating on the surface of samples with hydrochloric acid. Secondly, measure the samples by electronic scale again and the weight of the zinc coating is obtained (The first weighing result minus the second weighing result). Finally, Zinc coating weight is divided by surface area and finally zinc coating weight per unit area is obtained ( $\text{g}/\text{m}^2$ ).

After zinc bath, the whole parameters mentioned above can influence Zinc coating thickness. However, in the actual engineering application, the knife-lip clearance, air-knife height and air knife angle are basically steady. So optimization of these process parameters has no obvious practical significance. Air pressure, the knife-stripe distance and strip velocity can be easily controlled by workers or machines, and theory and practice have also proved that these three parameters have more significant impact on the thickness of zinc coating than other parameters [9]. In hot-dip galvanizing process, air pressure is the most sensitive parameter and an important process in the control of coating thickness. In general, when the air pressure becomes smaller, the zinc thickness will become bigger. However, on the condition of very low strip velocity, sometimes, when air pressure becomes bigger, the zinc thickness is greater. It is because the cooling effect of spray gas on zinc solution exceeds its zinc blowing effect, resulting in rapid solidification of zinc coating. Under the premise that other conditions remain unchanged, the coating thickness will become bigger when the strip velocity is increased [31]. Moreover, the change of strip velocity will affect the air pressure. Besides, the knife-stripe distance has a very significant influence on the thickness of zinc coating [31]. The greater

Items	Values
Iron content	0.0077%
Aluminium content	0.4%
Air-knife height	220mm
Air-knife angle	$90^\circ$
Knife lip clearance	0.6-0.8mm
Zinc bath temperature	$460^\circ\text{C}$

Table 1: Specifications of hot-dip galvanizing process.

the distance between the air knife and the strip, the greater the thickness of the zinc coating is.

In this experiment, three factors were considered, and the CCD design was determined with 8 cube points, 6 star points and 6 center points. There were 20 sets of experiments. The strip speed, blowing pressure and the distance between the cutter and the strip surface were recorded as X1, X2, X3, respectively. According to the actual production practice of Tianjin sea steel plate Co., Ltd. and related literature, the two level of the three factors value is shown in Table 2.

In response surface, linear model and polynomial model are the most commonly used models to establish the correlation among factors. The usual practice is to firstly fit a linear regression equation with the experimental data, if it is found that the bending trend, try to fit a quadratic regression equation. The general forms of the two kinds of models were listed as follows:

First order linear regression model:

$$Y = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + \dots + \beta_k X_k + \varepsilon$$

Where Y is the response variable;  $X_i$  is the explanatory variables;  $\beta_0$  is the model constant;  $\beta_i$  represents the linear coefficient; and  $\varepsilon$  is the statistical error.

Two order polynomial regression model:

$$Y = \beta_0 + \sum_{i=1}^K \beta_i X_i + \sum_{i=1}^K \beta_i X_i^2 + \sum \sum_{i < j} \beta_{ij} X_i X_j + \varepsilon$$

Where Y is the response variable;  $X_i$  is the explanatory variables;  $\beta_0$  is the model constant;  $\beta_i$  represents the linear coefficient; and  $\varepsilon$  is the statistical error.

In the CCD experiment, 20-run trials were conducted by Design Expert. The number of central points was 6, and the alpha value was 1.68179. Select the "Cube Points" in the Levels Define column, which is to choose the CCC design (central composite sequential design), and the asterisk will go beyond the cube. Finally, the experimental order was randomized. The result of experiment is presented in Table 3.

In order to select the highest fitness model, 4 different sources of regression models were carried out including Linear, 2FI, Quadratic, Cubic. Result analysis and summary could be showed in Table 4.

It can be seen from Table 4 that the fitting effect of polynomial model is the best, p-value equals 0.0006, far less than 0.01. In addition, the p-value of the 'Lack of Fit' is 0.175, which is far greater than 0.05, which indicates that lack of fit does not exist. Finally, in the preliminary diagnosis, multivariate full correlation coefficient R2 (R-sq) of the polynomial model is 96.08%, and the modified multivariate full correlation coefficient R-sq (adj) is 92.56%, which proves that the model has higher explanatory level for variables. Except for the polynomial model, the other 3 models, including linear regression model, all show a certain mismatch phenomenon, and the modified multivariate full correlation coefficient R-sq (adj) is not high, which proves that variables cannot be effectively explained. Moreover, the R-sq value of Cubic fitting model has obvious abnormal, which indicates that the prediction effect is very poor. Therefore, it can be preliminarily determined that polynomial model is the most suitable for modeling.

	X1(m/min)	X2 (MPa)	X3(cm)
-1	40	0.4	23
1	60	0.5	25

Table 2: Levels of three factors in CCD experiment.

Run no.	Strip velocity (m/min)	Air pressure (MPa)	The distance (cm)	Zinc thickness (g/m <sup>2</sup> )
1	60	0.4	25	116
2	50	0.45	24	92
3	40	0.5	23	41
4	50	0.45	25.68	120
5	66.82	0.45	24	94
6	50	0.53	24	81
7	60	0.5	25	96
8	40	0.4	23	55
9	50	0.37	24	100
10	50	0.45	24	96
11	40	0.5	25	81
12	33.18	0.45	24	56
13	50	0.45	24	103
14	60	0.5	23	76
15	60	0.4	23	90
16	50	0.45	24	93
17	40	0.4	25	99
18	50	0.45	22.32	79
19	50	0.45	24	95
20	50	0.45	24	99

Table 3: The result of first experiment.

			Adjusted	Predicted	Lack of	F	Sequential
Source	df	R-Squared	R-Squared	R-Squared	p-value	Value	p-value
Linear	11	0.7671	0.7234	0.6203	0.013	8.85	< 0.0001
2FI	8	0.7935	0.6982	0.3744	0.0091	10.71	0.6541
Quadratic	5	0.9608	0.9256	0.7734	0.175	2.44	0.0006
Cubic	1	0.9724	0.9126	-2.5919	0.0444	7.13	0.6606

Table 4: Summary of regression analysis.

No.	X1(m/min)	X2(MPa)	X3(cm)
1	40	0.4	23
2	50	0.45	24
3	60	0.5	25

Table 5: Levels of three factors in Taguchi experiment.

### Design of Taguchi experiment

In this part, Taguchi method was used to do the system robustness analysis and verify the conclusion from RSM. One group of experiment was carried out in this research (L9 (3<sup>4</sup>) orthogonal table was selected). As for the levels of influence factors, the air pressure was set as 0.4 MPa, 0.45 MPa and 0.5 MPa, the strip velocity was set as: 40 m/min, 50 m/min, 60 m/min and the range of air knife was set as 23 mm, 24 mm and 25 mm. The three factors (strip velocity, air pressure, the range of air knife and ) chosen for this Taguchi experiment were designated as X1, X2, X3, showed in Table 5.

The errors of three independent variables were treated as the error factor, and the error value depended on the numerical value itself. In this experiment, the three error levels of X1, X2 were listed as follows:

Second level=internal standard center value;

First level=inner table center value \* (1-10%);

Third level=inner table center value \* (1+10%).

According to the result of RSM, the range of air knife had a great influence on the thickness of zinc layer and actually the fluctuation was small. Therefore, the three error levels of independent variable X3 were listed as follows:

Second level=internal standard center value;

First level=inner table center value \* (1-3%);

Third level=inner table center value \* (1+3%).

Then, in order to reduce the number of experiments, this part used “the most unfavorable comprehensive error method” to design noise table, which included a total of 18 experiments. Considering the characteristic (‘look at the target’) of the response variable “zinc layer thickness” and the actual production practice, the comprehensive error factor N’ was taken as the following two levels:

N1’: the worst side of the negative side;

N2’: the worst side of the positive side.

Therefore, the final noise table generated was shown in Table 6 and the final experiment result could be seen in Table 7.

### Design of Genetic Algorithm optimization

The thickness requirements of zinc layer are stipulated by customers. Therefore, how to set the parameters of air knife to make the ultimate zinc layer thickness closer to the target value is the main problem. In this paper, the genetic algorithm (GA) was used to find the optimal parameters of air knife under the specified zinc thickness target in the hot galvanizing process, and the fitness function (1) was established as follows:

$$val_1 = \min|Y - d| \tag{1}$$

Where Y is the theoretical value calculated by our model; d is

NO.	X1 (m/min)	X2 (MPa)	X3 (cm)
1	40.5	0.44	23.28
2	49.5	0.36	24.72
3	40.5	0.495	23.765
4	49.5	0.405	25.235
5	40.5	0.55	24.25
6	49.5	0.45	25.75
7	45	0.44	23.765
8	55	0.36	25.235
9	45	0.495	24.25
10	55	0.405	25.75
11	45	0.55	23.28
12	55	0.45	24.72
13	49.5	0.44	24.25
14	60.5	0.36	25.75
15	49.5	0.495	23.28
16	60.5	0.405	24.72
17	49.5	0.55	23.765
18	60.5	0.45	25.235

Table 6: Noise table of Taguchi experiment.

No.	X1 (m/min)	X2 (MPa)	X3 (cm)	y1 (g/m <sup>2</sup> )	y2 (g/m <sup>2</sup> )	SNRA	STDE	MEAN
1	40	0.4	24	62	105	8.7747	30.4056	83.5
2	40	0.45	24.5	61	121	6.6281	42.4264	91
3	40	0.5	25	50	127	4.2194	54.4472	88.5
4	50	0.4	24.5	82	118	11.8842	25.4558	100
5	50	0.45	25	81	132	9.4059	36.0624	106.5
6	50	0.5	24	42	112	3.8382	49.4975	77
7	60	0.4	25	105	121	19.9895	11.3137	113
8	60	0.45	24	70	110	10.054	28.2843	90
9	60	0.5	24.5	62	110	8.0754	33.9411	86

Table 7: The result of Taguchi experiment.

the required value from customers; val represent absolute value of difference between theoretical value Y and the required value d.

From this fitness function, a conclusion can be obtained that the value of val<sub>1</sub> will be smaller when the Y is more close to the d. When the Y is equal to d, the val will reach zero, which is the best situation.

In addition, according to the Taguchi experiment, a large S/N (signal to noise ratio) represents a good system robustness because of the definite purposed character in three stage design. So except for the demand of customers, S/N should be considered as a part of the other fitness function, which could be showed as follows:

$$val_2 = \min(S / N) \tag{2}$$

Where the target is to make the S/N smaller to improve the system robustness.

Therefore, according to the result of Taguchi experiment, the equation of fitness function was established as follows:

$$val_1 = \min(|Y - d| + (S / N)) \tag{3}$$

Then, in actual production process of Tianjin sea steel plate Co., Ltd., the air pressure is usually maintained between 0.3 MPa and 0.6 MPa, the range of air knife is maintained between 22 cm and 27 cm. The strip speed of production line is generally maintained between 30 m/min and 60 m/min. The setting target of zinc thickness is not over 120 g/cm<sup>2</sup>.

In this paper, the binary encoding method was adopted. For example: air pressure is 0.36 MPa, strip speed is 50 m/min, air knife range is 24.5 cm. Take integer 36, 50, 45 for binary coding, the corresponding binary number is “100100”, “110010”, “101101”, the final formation of the chromosome as shown in Figure 3.

After the encoding is completed, genetic operations need to be designed, including selection, crossover and mutation operations. (1) *Selection*: The selection operation needs to select a pair of chromosomes from the current population. In order to keep the individuals with higher fitness to the next generation, this paper adopted roulette method and elitist reservation strategy to perform the selection operation. (2) *Crossover*: Crossover operation is the main operation process of generating new individuals in genetic algorithm. It exchanges some chromosomes between two individuals with a certain probability. In this paper, the method of “single point crossover” was adopted. The specific operation process was: firstly, the population is randomly paired, and then the intersection point was set randomly, and finally some genes were exchanged between pairs of chromosomes.

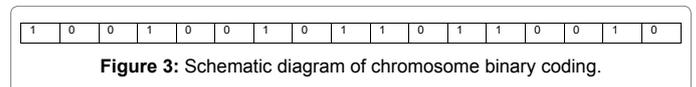


Figure 3: Schematic diagram of chromosome binary coding.

(3) *Mutation*: Mutation operation is to change the gene value of one or some loci in a small probability, and it is also an operation method to produce new individuals. The method of “basic bit variation” was used to perform the mutation operation. The specific operation process was: firstly, the mutation point of each individual was generated randomly, and then the original gene value of mutation point was inverted according to a certain probability. The setting values of experimental parameters in this paper can be showed in Table 8.

## Results and Discussions

### Results of RSM

Based on RSM, this paper used polynomial model for data fitting and considered the interactions between the three variables. After eliminating the no-significant effects, the results of variance analysis were shown in Table 9 and the final polynomial model was:

$$Y = -1425 + 22.14X_1 + 1314X_2 + 40.0X_3 - 0.0953X_1^2 - 1620X_2^2 - 0.475X_1X_3 \quad (4)$$

The P-Value of the corresponding regression item was 0 (<0.001), which indicates that the original hypothesis should be rejected, and the model was effective. Then, look at the following aspects: (1) The P-Value equals 0.307 of Lack of Fit is greater than the P-Value before removing the interaction item (0.175). It showed that the original hypothesis cannot be rejected, and it can be concluded that there is no phenomenon of mismatch in the model; (2) After removing several interaction terms, the multivariate full correlation coefficient R2 (i.e., R-sq) was 95.90%, and the modified multivariate full correlation coefficient R-sq (adj) was 94.01%. The results showed that the regression effect was good; (3) The s value was 480426. Actually, the s value of the model was lower than that of the model before the interaction is removed (5.35396). It was proved that the polynomial model had better fitting effect when the three interaction items were removed; (4) The significance of interaction effect could be seen from Table 5. The square terms of blowing pressure and strip speed were still highly significant, and the interaction term of strip speed and air knife range was also highly significant.

In order to verify the accuracy of log regression model, scatter plot of residuals was showed in Figure 4 and the normal probability plot of

Parameters	Setting value
Population size	100
Generation gap	0.9
Cross rate	0.9
Mutation rate	0.3
Maximum genetic algebra	50

Table 8: Experiment parameters of GA.

Variables	DF	Adj SS	Adj MS	F-value	p-value
Model	6	7021.75	1170.29	50.70	0.000
$x_1$	1	2015.51	2015.51	87.32	0.000
$x_2$	1	702.58	702.58	30.44	0.001
$x_3$	1	2898.36	2898.36	125.57	0.000
$x_1^2$	1	1130.38	1130.38	48.97	0.000
$x_2^2$	1	161.65	161.65	7.00	0.020
$x_1x_3$	1	180.50	180.50	7.82	0.015
Error	13	300.05	23.08		
Lack of fit	8	216.72	27.09	1.63	0.307
Pure Error	5	83.33	16.67		
Total	19	7321.80			

Table 9: The results of variance analysis.

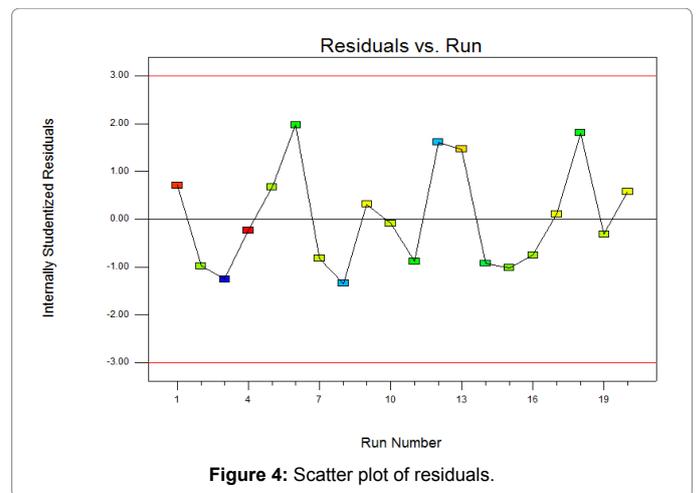


Figure 4: Scatter plot of residuals.

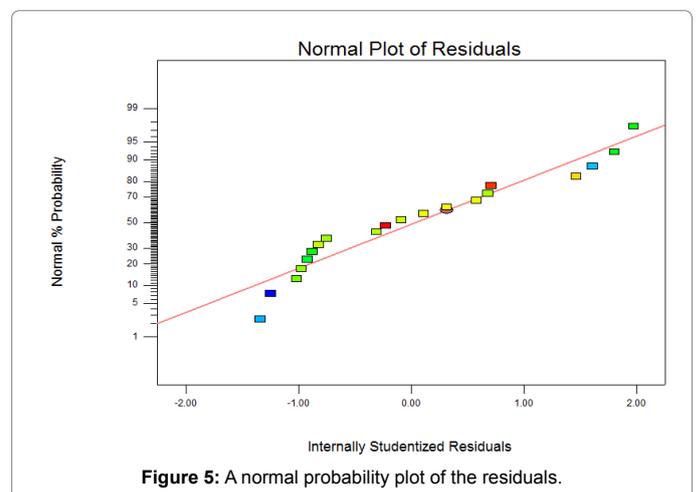


Figure 5: A normal probability plot of the residuals.

the residuals was depicted in Figure 5. Figure 4 showed the residuals in the order of the observed values, and the results were in line with expectations. From Figure 5, the figure reveals that the residuals generally fall on a least-square line which is used to estimate the cumulative distribution function for the population [22]. As evident from the figure, the errors can be regarded as normal distribution and there are almost no apparent violations of the assumptions that underlie the analysis [32]. By displaying a satisfactory normal distribution, the normality assumptions made earlier could be confirmed and the predictive regression model has extracted all information available from the experimental data [33].

Overall, when the strip speed increases from 40 m/min to 50 m/min, the thickness of zinc steel increases; but when the strip speed exceeds 50 m/min and continues to increase, the thickness of zinc remains unchanged, even has a slight downward trend. When the air pressure increases from 0.4 MPa to 0.45 MPa, the thickness of zinc has a slight downward trend, but not obvious; when the gas pressure exceeds 0.45 MPa, the thickness of zinc decreases quickly and the downward trend is more and more obvious. With respect to the range of the air knife, the thickness of the zinc layer increases with the range of the range of air knife quickly. The relationship between strip speed, blow pressure, range of air knife and thickness of zinc coating is shown in Figures 6-8.

According to the above experimental results, the response surface diagram of strip speed, the range of air knife and response variable

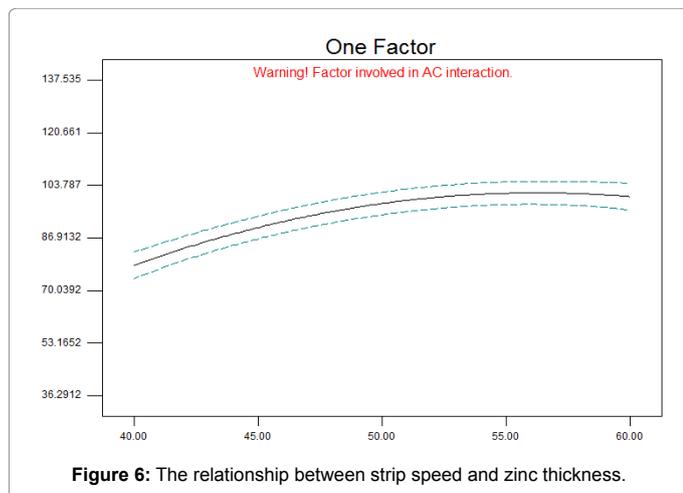


Figure 6: The relationship between strip speed and zinc thickness.

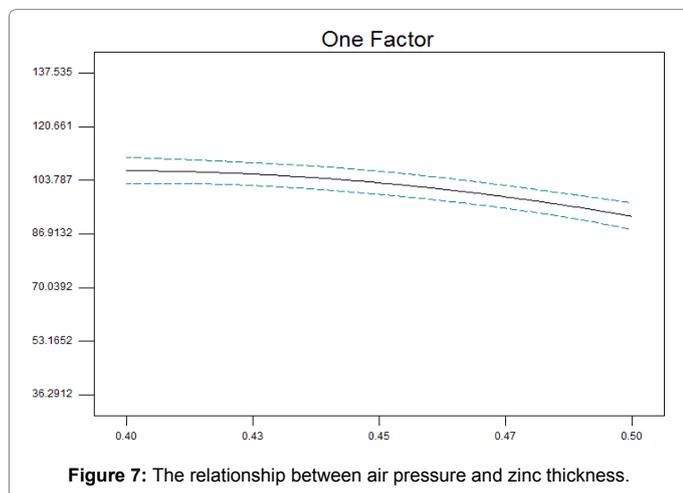


Figure 7: The relationship between air pressure and zinc thickness.

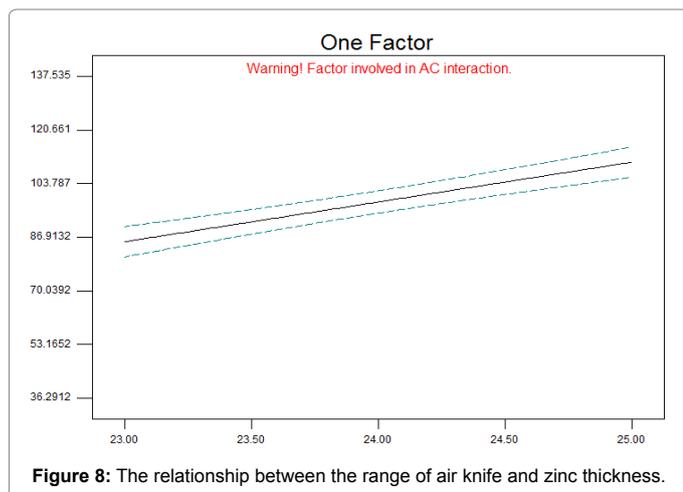


Figure 8: The relationship between the range of air knife and zinc thickness.

could be made, as shown in Figures 8 and 9. On the one hand, when the strip speed increased from 40 m/min to 50 m/min, the zinc thickness increased, but the increase was obviously affected by the range of air knife: (1) when the range of air knife was between 23 mm and 24 mm, the zinc thickness increased rapidly with the steel speed; (2) when the range of air knife is over 24 mm, the zinc thickness increased slowly with the steel speed. On the other hand, when the strip speed exceeded

50 m/min, the zinc thickness was less affected by the change of strip speed, but also affected by the range of air knife: (1) when the air knife range was between 23 mm-24 mm and the steel speed increased from 50 m/min to 60 m/min, the zinc thickness stayed unchanged; (2) when the range of air knife was more than 24 mm and the strip speed increased from 50 m/min to 60 m/min, the thickness of zinc appeared to decrease. So Figure 8 apparently shows that there is a certain interaction between strip speed and air knife range. In addition, from Figure 9, the two curves (, the red line represents the relation between air knife range and zinc layer thickness and the black line represents the relation between strip speed and zinc layer thickness) are not parallel, but show a certain angle, it is further proved that the interaction between strip speed and air knife range.

### Results of Taguchi experiment and system robustness analysis

Through Minitab, the experimental results of signal-to-noise ratio (S/N), mean and standard deviation were shown in Tables 10-12. Since the choice of the Taguchi design, the divergence factor should be chosen to minimize the divergence, and then the level of the adjustment factor was selected to make the zinc layer thickness reach the target value.

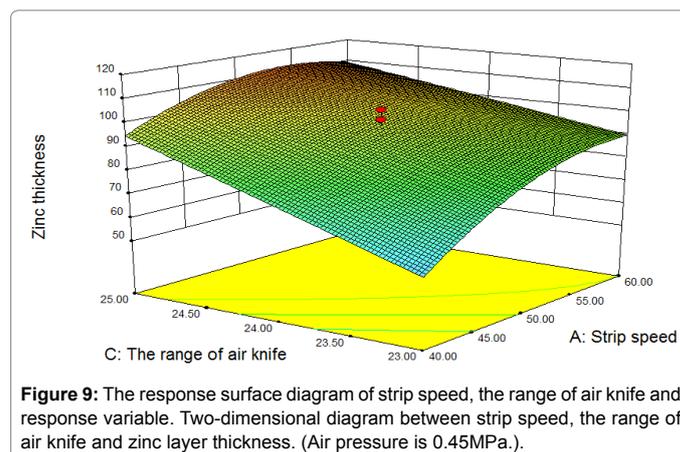


Figure 9: The response surface diagram of strip speed, the range of air knife and response variable. Two-dimensional diagram between strip speed, the range of air knife and zinc layer thickness. (Air pressure is 0.45MPa.)

Level	X1 (m/min)	X2 (MPa)	X3 (cm)
1	6.541	13.549	7.556
2	8.376	8.696	8.863
3	12.706	5.378	11.205
Delta	6.166	8.172	3.649
Rank	2	1	3

Table 10: S/N response table (Nominal is best ( $10 \times \log_{10} (\bar{Y}^2/s^2)$ )).

Level	X1 (m/min)	X2 (MPa)	X3 (cm)
1	87.67	98.83	83.5
2	94.5	95.83	92.33
3	96.33	83.83	102.67
Delta	8.67	15	19.17
Rank	3	2	1

Table 11: Mean response table.

Level	X1 (m/min)	X2 (MPa)	X3 (cm)
1	42.43	22.39	36.06
2	37.01	35.59	33.94
3	24.51	45.96	33.94
Delta	17.91	23.57	2.12
Rank	2	1	3

Table 12: Standard deviation table.

In this Taguchi design, the signal-to-noise ratio (S/N) increases, the system robustness is better.

According to the signal-to-noise ratio table, the Mean value and range of the signal-to-noise ratio (SNR) could be seen. According to the order ranging from large to small, the influence of various factors on SNR was judged. The arrangement order was: (1) Air pressure, (2) Strip speed, (3) Air knife range. Obviously, the air pressure was the dispersion factor. According to the mean response table, the arrangement sequence was listed as follows: (1) Range of air knife, (2) Air pressure, (3) Strip speed. Because the range of air knife has the greatest influence on the mean, and it is not the divergence factor, the range of air knife could be judged as the position factor. In addition, Figures 10 and 11 also confirmed our conclusions.

Figure 10 showed that in the curve between the air pressure and zinc layer thickness is the most steep, which means air pressure has the biggest influence on the signal-to-noise ratio. Figure 11 showed that the range of air knife has the biggest influence on the mean of zinc thickness. So, two conclusions could be obtained via the results of Taguchi experiment: (1) The air pressure should be taken into account

firstly when workers need to set values of parameters. From Figure 10, it could be seen that the signal to noise ratio decreased linearly with the increase of air pressure. Therefore, the air pressure should be kept at a lower level; (2) After determining the level of air pressure, the range of air knife should be considered secondly to reach the target.

### Verification of polynomial model

Figure 11 also showed that the similar conclusions with RSM. When the strip speed increases from 40 m/min to 50 m/min, the thickness of zinc steel increases; but when the strip speed exceeds 50 m/min and continues to increase, the thickness of zinc remains unchanged, even has a slight downward trend. When the air pressure increases from 0.4 MPa to 0.45 MPa, the thickness of zinc has a slight downward trend, but not obvious; when the gas pressure exceeds 0.45 MPa, the thickness of zinc decreases quickly and the downward trend is more and more obvious. With respect to the range of the air knife, the thickness of the zinc layer increases with the range of the range of air knife quickly. So to a certain extent, it proved the correctness and reliability of polynomial model. Then, the thickness data obtained from Taguchi experiment were compared with the data calculated by polynomial model and the

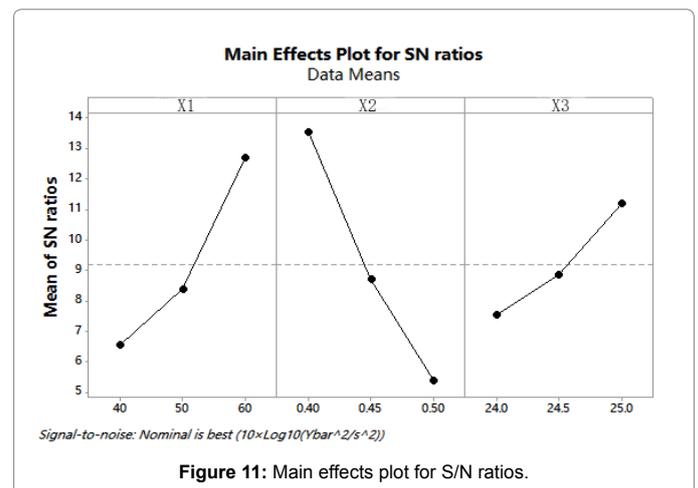
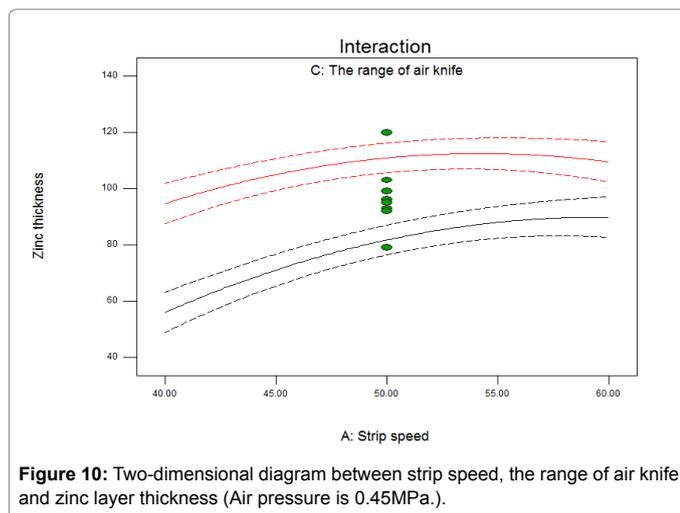


Figure 10: Two-dimensional diagram between strip speed, the range of air knife and zinc layer thickness (Air pressure is 0.45MPa.).

Figure 11: Main effects plot for S/N ratios.

NO.	X1 (m/min)	X2 (MPa)	X3 (cm)	Real thickness (g/m <sup>2</sup> )	Calculated thickness (g/m <sup>2</sup> )	Error (g/m <sup>2</sup> )	Error percentage (%)
1	40.5	0.44	23.28	62	63.23	-1.233	-1.99
2	49.5	0.36	24.72	105	108.08	-3.080	-2.93
3	40.5	0.495	23.765	61	62.26	-1.264	-2.07
4	49.5	0.405	25.235	121	119.93	1.067	0.88
5	40.5	0.55	24.25	50	51.49	-1.495	-2.99
6	49.5	0.45	25.75	127	125.22	1.776	1.40
7	45	0.44	23.765	82	85.47	-3.469	-4.23
8	55	0.36	25.235	118	117.64	0.359	0.30
9	45	0.495	24.25	81	83.46	-2.463	-3.04
10	55	0.405	25.75	132	128.15	3.852	2.92
11	45	0.55	23.28	42	44.56	-2.558	-6.09
12	55	0.45	24.72	112	110.66	1.342	1.20
13	49.5	0.44	24.25	105	101.77	3.229	3.08
14	60.5	0.36	25.75	121	118.75	2.254	1.86
15	49.5	0.495	23.28	70	74.74	-4.740	-6.77
16	60.5	0.405	24.72	110	110.51	-0.507	-0.46
17	49.5	0.55	23.765	62	61.90	0.103	0.17
18	60.5	0.45	25.235	110	113.11	-3.107	-2.82

Table 13: The comparison table between real values and calculated values of coating weight.

results were shown in Table 13. Then, the percentage error is expressed by histogram, as shown in Figure 12.

Figure 12 showed that the fitting accuracy of the polynomial model was between (-7%)-(3%), which could meet the actual requirements and proved the accuracy of RSM. And Figure 13 showed that the average error of zinc thickness was growing with the increase of air pressure, which meant that stability of air knife system decreased and proved the accuracy of Taguchi experiment.

### Results of genetic algorithm

According to the results from RSM and Taguchi experiment, the final fitness function could be seen as follows:

$$val = \min(|y - d| + (x_2 - a)) \quad (5)$$

Where  $y$  is the calculated value from polynomial model,  $d$  is determined by customers,  $a$  equals the permitted minimum value of air pressure, which is usually an empirical value,  $x_2$  is the actual setting value of air pressure.

According to Taguchi experiment, air pressure is dispersion factor, which has the biggest influence on the system robustness. When the value of air pressure decreases, the S/N increases and the system robustness increases. So in the final fitness function, the type  $(x_2 - a)$  was used to express the requirement of system robustness. In this paper, according to the actual production situation of a certain steel company, the value of  $a$  set as 0.3 MPa. And the value of  $d$  was not over 120 g/m<sup>2</sup>. When  $d$  equals 100 g/m<sup>2</sup>, the optimal solution was obtained, after

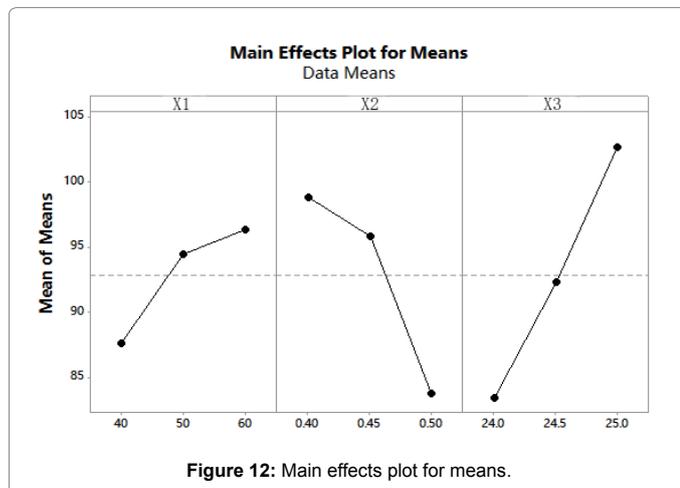


Figure 12: Main effects plot for means.

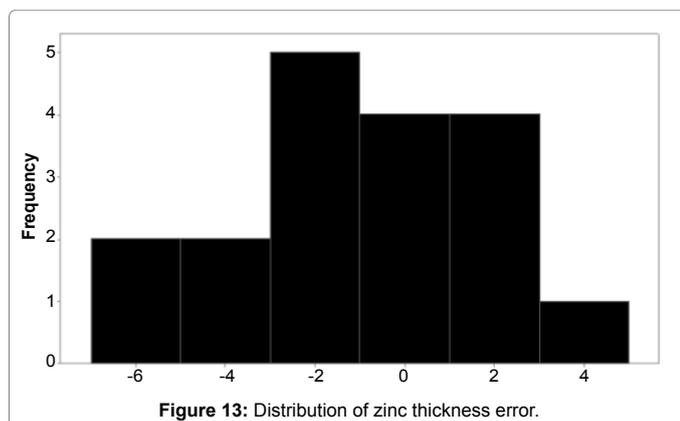


Figure 13: Distribution of zinc thickness error.

50 iterations (5 seconds). The value of val was 0.1022, which means the value of  $Y$  was 100.03 g/m<sup>2</sup>. It was very close to the value of  $d$  (100 g/m<sup>2</sup>). The optimal parameter combination of air knife was also obtained. The value of strip velocity was 54 m/min. The value of air pressure was 0.37 MPa. The value of strip to knife distance was 23.9 cm. Finally, the change curve of solution and population mean could be showed in Figures 14 and 15 to prove the validity of genetic algorithm.

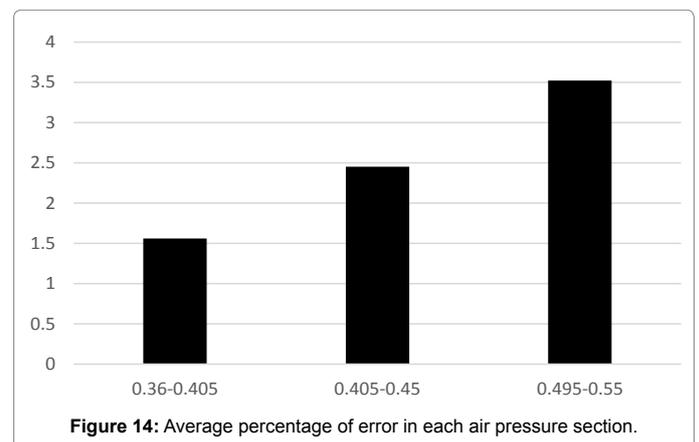


Figure 14: Average percentage of error in each air pressure section.

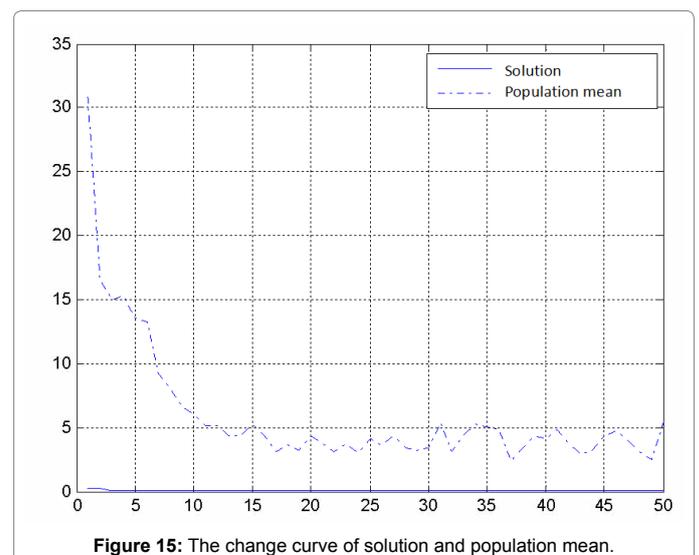


Figure 15: The change curve of solution and population mean.

### Conclusion

In the hot galvanizing process, whether the zinc coating thickness meets the customer demands is the key to determine the product quality. In this paper, a integrated method including RSM, Taguchi experimental design and GA were carried out to research the relationship among variables and system robustness. Air pressure, the range of air knife and strip velocity were exploratory variables and the zinc thickness was the response variable. The conclusions of our research can be listed as follows:

- (1) The polynomial model established by RSM has been verified via real data and the prediction error of polynomial model is between (-7%)-(3%), which could meet the actual requirements. Besides, this paper deeply analyzed the interaction effect between the range of air knife and strip speed via RSM. The effect of strip speed on zinc layer thickness is affected by the range of air knife.

(2) This paper used Taguchi method to analyze the system robustness and found that the air pressure was the dispersion factor, which had the biggest influence on the system robustness and should be considered firstly. The range of air knife was the position factor, which had the biggest influence on the mean value of zinc thickness and should be considered secondly.

(3) According to the conclusions of RSM and Taguchi method, a comprehensive fitness function was built and the relevant constraints were defined. Then, this paper used genetic algorithm to find the optimal parameter combination under the given coating thickness, which could be regarded as a good tool to predict the reasonable values of parameters to reach the target.

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