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Quality Improvement for Steel Wire Coating by the Hot-Dip Galvanizing Process to A Class Standard: A Case Study in a Steel Wire Coating Factory

Pongthorn Ruksorn* and Prapaisri Sudasna-na-Ayudthya

ABSTRACT

Demand for steel wire zinc coating by galvanizing to the A class standard is increasing because it protects the wire rod from corrosion. It can be applied to various types of products used in electrical equipment and construction. There are several factors and their levels in the hot-dip galvanizing process that affect the quality of A class galvanized steel wire such as the zinc bath temperature and withdrawal speed. If these factors and their levels are not properly controlled, the mass of zinc coating used will be more than the required standard (greater than 259 g.m^{-2}). The objective of this research was to apply a 2^k split-plot experiment to study the effects of factors on the hot-dip galvanizing process to the A class standard. The results showed that the interaction between the zinc bath temperature with each of the charcoal wiping condition, the free zinc length and the withdrawal speed, and the interaction between the charcoal wiping condition and each of the free zinc length and the withdrawal speed significantly affected the mass of zinc coating in the hot-dip galvanizing process to the A class standard. Thus, the appropriate settings were determined to reduce the mass of zinc coating. The confirmation results indicated that after applying the new settings, the mass of zinc coating conformed to the required standard.
Keywords: hot-dip galvanizing, mass of zinc coating, steel wire, split-plot experiment

INTRODUCTION

Hot-dip galvanized zinc coating is one of the techniques frequently used for protecting steel against corrosion and it has been applied in various fields such as the automobile and construction industries (Marder, 2000). Previous researchers showed that many factors such as the aluminum concentration in the zinc bath (De Abreu *et al.,* 1999), the withdrawal speed (Ben nasr *et al.,* 2008), the zinc bath temperature (Bicao *et al.*, 2008; Jianhug *et al.*, 2009) and air-knife wiping (Zhang *et al.*, 2012) significantly affected the coating in hot-dip galvanizing.

Steel wire zinc coating by the hot-dip galvanizing process is based on factors and their levels that affect the quality of the steel wire such as the zinc bath temperature, the steel wire diameter and the withdrawal speed (Szota, 1995). If these factors and their levels are not properly controlled, the mass of zinc coating used is more than necessary to meet the required standard of TIS 404-2540 (1997) (Thai Industrial Standards Institute, 1998). Thus, the production cost is unnecessarily high. However, if the mass of zinc coating is less than 259 g.m^{-2}, the steel wire will erode. The objective of this research was to study the factors and their levels that affect the mass of

Department of Industrial Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand.
* Corresponding author, e-mail: tong0858@hotmail.com

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zinc coating in the hot-dip galvanizing process to the A Class standard.

MATERIAL AND METHODS

The experiment was carried out using low-carbon steel wire with a diameter of 3.00 mm. The galvanizing test was conducted in a furnace operating with at least 99.95% zinc. The stages prior to the galvanizing test—degreasing, pickling, rinsing and fluxing—were controlled in the appropriate solutions. Four control factors were investigated: zinc bath temperature (A), charcoal wiping condition (B), free zinc length (C) and withdrawal speed (D) according to the previous study on the mass of zinc coating on hot-dip galvanizing process to the C class standard (Thanprasertkul, 2010). A 2^k split-plot experiment (Montgomery, 2009) was employed to collect data.

However, it was not possible to completely randomize the order of runs for the zinc bath temperature and the charcoal wiping condition since the settings were difficult to change. Thus, they were assigned in whole plots. The rest of the factors—the free zinc length and withdrawal speed—were able to be completely randomized for the order of runs. Thus, they were assigned in subplots. The experimental plan was to divide the control factors into two levels of low (-1) and high (+1) using the values specified in Table 1. The experiment was run with two replicates. Thus, the total number of runs was 32 in this study.

Before performing the analysis of variance (ANOVA), it was necessary to verify the assumptions of residual analysis including a normal distribution, zero mean, constant variance and independence (Montgomery, 2009). The normality assumption was checked by investigating a normal probability plot of the residuals. If the graph resembles a straight line, then the normality assumption is satisfied. A plot of the residuals versus fitted values was used to check the assumption of a zero mean and constant variance. If the residuals are randomly distributed around the axis, then the residuals have a zero mean and constant variance. A plot of the residuals in time sequence was used to check the independence assumption. If the residuals are randomly distributed (having no pattern), then the residuals are independent.

After it was confirmed that all assumptions were met, the hypothesis testing was performed. The hypotheses were:

(i) Hypothesis testing for the main factor

H_0: the main factor has no influence on the mass of zinc coating

H_1: the main factor has an influence on the mass of zinc coating

(ii) Hypothesis testing for the interaction factor

H_0: the interaction factor has no influence on the mass of zinc coating

H_1: the interaction factor has an influence on the mass of zinc coating

If the *P*-value is smaller than the significance level of 0.05, the null hypothesis will be rejected (Montgomery *et al.*, 2012) with 95% confidence and the factor being considered has an influence on the mass of zinc coating.

In this research, Minitab statistical

Table 1 Factors and their levels for 2^k split-plot experiment.

Factor	Level	
	Low (-1)	High (+1)
Zinc bath temperature (°C)	430	450
Charcoal wiping condition (min)	30	90
Free zinc length (cm)	5	15
Withdrawal speed (m.min^{-1})	10	20

software (Version 16; Minitab Inc.; State College, PA, USA) was used to perform residual analysis to check the assumptions of normal distribution, zero mean, constant variance and independence of the residuals.

RESULT AND DISCUSSION

Figure 1 shows that the model was adequate. The residuals were normally distributed with a zero mean and constant variance. They were independent. Therefore, the four assumptions were met and the analysis of variance was conducted for the 2^k split-plot experiment.

The results from the ANOVA are shown in Table 2.

In Table 2, R(AB) indicates the whole plot error that was the variability between whole plots run under the same zinc bath temperature (A) and charcoal wiping condition (B). The whole plot error was used to calculate the F statistics for the zinc bath temperature (A), the charcoal wiping condition (B) and the interaction between the zinc bath temperature and charcoal wiping condition (AB). The results in Table 2 indicate that all of the two-factor interaction terms were significant at the $P < 0.05$ level except for the interaction between the free zinc length and the withdrawal speed (CD). The interaction between the zinc bath temperature and charcoal wiping condition (AB), the interaction between the zinc bath temperature and the free zinc length (AC), the interaction between the zinc bath temperature and the withdrawal speed (AD), the interaction between the charcoal wiping condition and the free zinc length (BC) and the interaction between the charcoal wiping condition and the withdrawal speed (BD) significantly affected the mass of zinc coating since their *P*-values were smaller than the test significance level of 0.05.

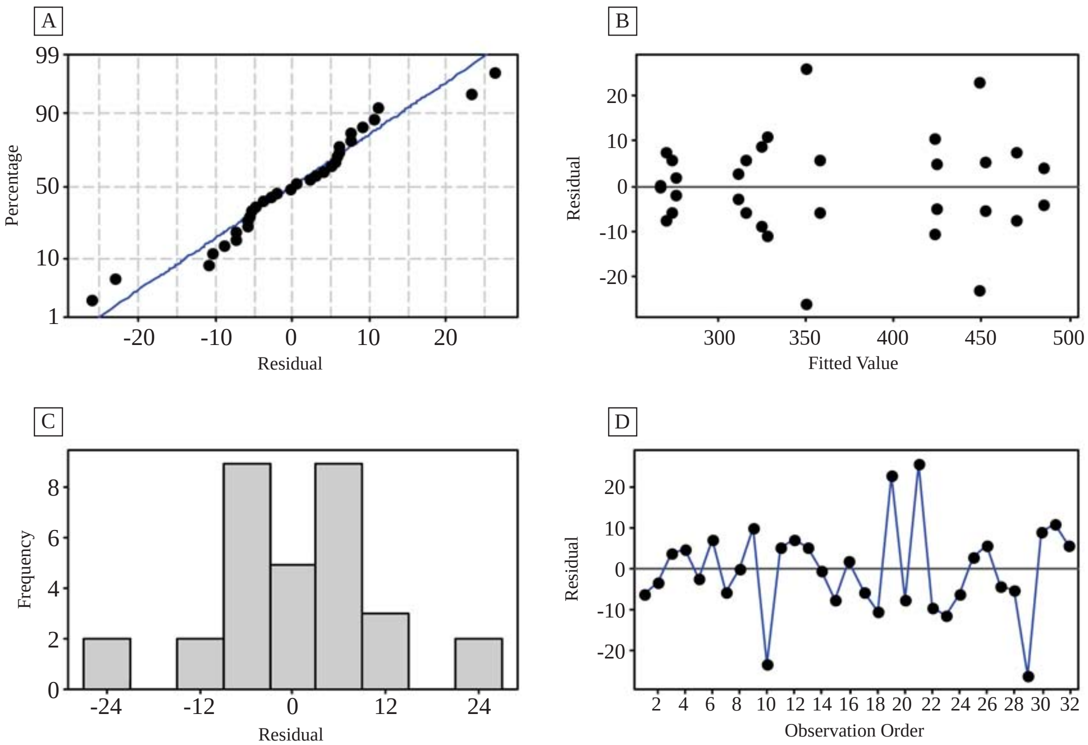

Figure 1 Residual plot analysis to check model adequacy for the mass of zinc coating: (A) Normal probability plot; (B) Histogram; (C) Residual versus fitted values; (D) Residuals plotted in observation order.

Table 2 Analysis of variance table for the mass of zinc coating.

Source	df	SS	MS	F	*P*-value
A	1	36.1	36.1	0.37	0.574
B	1	288.0	288.0	2.98	0.159
A*B	1	40328.0	40328.0	417.64	0.000*
R(AB)	4	386.2	96.6	0.32	0.860
C	1	21321.1	21321.1	70.43	0.000
D	1	54780.5	54780.5	180.96	0.000
A*C	1	9316.1	9316.1	30.77	0.000*
A*D	1	2964.5	2964.5	9.79	0.009*
B*C	1	3872.0	3872.0	12.79	0.004*
B*D	1	6216.1	6216.1	20.53	0.001*
C*D	1	200.0	200.0	0.66	0.432
A*B*C	1	1568.0	1568.0	5.18	0.042
A*B*D	1	6786.1	6786.1	22.42	0.000
A*C*D	1	648.0	648.0	2.14	0.169
B*C*D	1	19900.1	19900.1	65.74	0.000
A*B*C*D	1	11781.1	11781.1	38.92	0.000
Error	12	3632.7	302.7		
Total	31	184024.9			

Df = Degrees of freedom, SS = Sum of squares, MS = Mean sum of squares, F = F test statistic.
A = Zinc bath temperature, B = Charcoal wiping condition, C = Free zinc length, D = Withdrawal speed.
Interactions with an asterisk after their P-value are significant at $P < 0.05$.

As the two-factor interactions were significant, the main effects, the three-factor interactions and the four-factor interactions were not be considered (Sudasna-na-Ayudthya and Luangpaiboon, 2008; Montgomery, 2009). The interaction plots of the significant interaction terms are shown in Figures 2 to 6. These plots were used to determine the appropriate settings for the factors.

Figure 2 indicates that the zinc bath temperature (A) and the charcoal wiping condition (B) should be set at 430 °C and 30 min, respectively, to minimize the mass of zinc coating.

Figure 3 indicates that the zinc bath temperature (A) and the free zinc length (C) should be set at 430 °C and 5 cm, respectively, to minimize the mass of zinc coating.

Figure 4 indicates that the zinc bath temperature (A) and the withdrawal speed (D) should be set at 430 °C and 10 $m.min^{-1}$, respectively, to minimize the mass of zinc coating.

Figure 5 indicates that the charcoal wiping condition (B) and the free zinc length (C) should be set at 30 min and 5 cm, respectively, to minimize the mass of zinc coating.

Figure 6 indicates that the charcoal wiping condition (B) and the withdrawal speed (D) should be set at 30 min and 10 $m.min^{-1}$, respectively, to minimize the mass of zinc coating.

In summary, the appropriate parameters were zinc bath temperature (A) at 430 °C, charcoal wiping condition (B) at 30 min, free zinc length (C) at 5 cm and withdrawal speed (D) at 10 m/min. These parameters were applied to actual production in a confirmation test that was run with 20 replicates and the mass of the zinc coating value was recorded. From the confirmation test, the average of the mass of zinc coating was 300.45 $g.m^{-2}$ with a standard deviation of 39.27 $g.m^{-2}$. The 95% confidence lower bound of the mean of the mass of zinc coating was 285.27 $g.m^{-2}$.

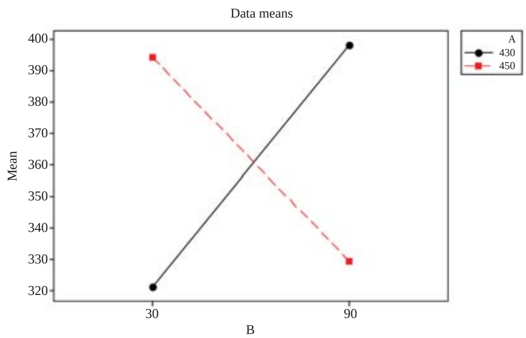

Figure 2 Interaction plot between zinc bath temperature (A at 430 and 450 °C) and charcoal wiping condition (B at times of 30 and 90 min).

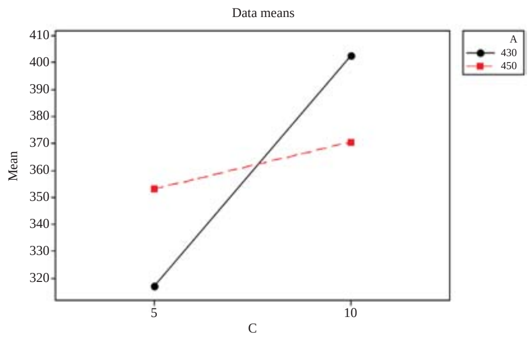

Figure 3 Interaction plot between zinc bath temperature (A at 430 and 450 °C) and free zinc length (C at 5 and 15 cm).

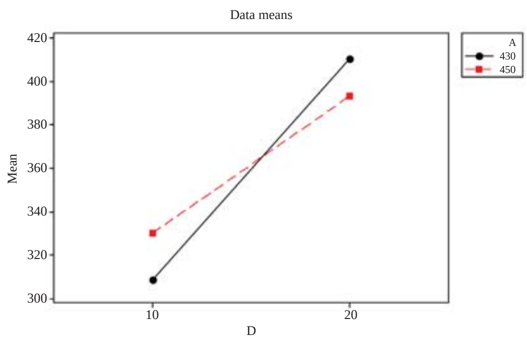

Figure 4 Interaction plot between zinc bath temperature (A at 430 and 450 °C) and withdrawal speed (D at 10 and 20 m.min^{-1}).

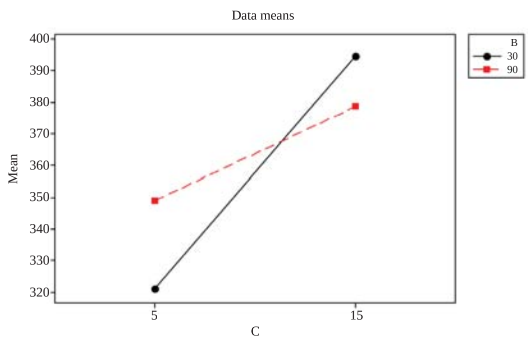

Figure 5 Interaction plot between charcoal wiping condition (B at 30 and 90 min) and free zinc length (C at 5 and 15 cm).

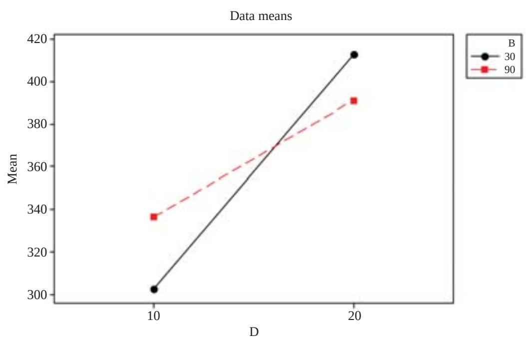

Figure 6 Interaction plot between charcoal wiping condition (B at 30 and 90 min) and withdrawal speed (D at 10 and 20 m.min^{-1}).

CONCLUSION

The objective of this research was to study the effects of factors and their levels in steel wire coating by hot-dip galvanizing process to the A class standard. A 2^k split-plot was used in this research. The main conclusions were:

1. All two-factor interaction terms were significant at the $P < 0.05$ level except for the interaction between the free zinc length and the withdrawal speed (CD). The interaction between the zinc bath temperature with each of the charcoal wiping condition, the free zinc length and the

withdrawal speed, and the interaction between the charcoal wiping condition and each of the free zinc length and the withdrawal speed significantly affected the mass of zinc coating.

2. The appropriate parameters to minimize the mass of coating were zinc bath temperature (A) at 430 °C, charcoal wiping condition (B) at 30 min, free zinc length (C) at 5 cm and withdrawal speed (D) at 10 m.min^{-1}. These settings produced an average mass of zinc coating of 300.45 g.m^{-2} and still conformed to the required standard.

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LITERATURE CITED

Ben nasr, J., A. Snouussi, C. Bradai and F. Halouani. 2008. Effect of the withdrawal speed on the thickness of the zinc layer in hot dip pure zinc coating. **Mater. Lett.** 62: 2150–2152.

Bicao, P., W. Jianhua, S. Xuping, L. Zhi and Y. Fucheng. 2008. Effects of zinc bath temperature on the coating of hot-dip galvanizing. **Surf. Coat. Technol.** 202: 1785–1788.

De Abreu, Y., A. Da Silva, A. Ruiz, R. Requiz, N. Angulo and R. Alanis. 1999. Study of zinc coatings on steel substrate attained by two different techniques. **Surf. Coat. Technol.** 120–121: 682–686.

Jianhua, W., T. Hao, P. Bicao, W. Xinming, Y. Fucheng and S. Xuping. 2009. The effects of zinc bath temperature on the coating growth behavior of reactive steel. **Mater. Charact.** 60: 1276–1279.

Marder, A.R. 2000. The metallurgy of zinc-coated steel. **Prog. Mater. Sci.** 45: 191–271.

Montgomery, D.C. 2009. **Design and Analysis of Experiment.** 7th ed. John Wiley & Sons, Inc. New York, NY, USA. 674 pp.

Montgomery, D.C., G.C. Runger and N.F. Hubele, 2012. **Engineering Statistics.** 5th ed. Wiley & Sons, Inc. New York, NY, USA.544 pp.

Sudasna-na-Ayudthya, P. and P. Luangpaiboon. 2008. **Design and Analysis of Experiments.** 1st ed. TOP Publishing, Bangkok, Thailand. 464 pp. [in Thai]

Szota, J.G. 1995. Steel wire galvanizing by the VERT-DOWN method. **J. Mater. Process. Technol.** 55: 134–139.

Thai Industrial Standards Institute. 1998. **Galvanized Steel Wire Strands.** TIS 404-2540 (1997). 1st ed. Ministry of Industry. Bangkok, Thailand. 9 pp. [in Thai].

Thanprasertkul, P. 2010. **Design of Experiment for Improving Steel Wire Coating by Hot-dip Galvanizing Process at C Class.** ME thesis, Kasetsart University, Bangkok, Thailand.

Zhang, Y., Q. Cui, F. Shao, J. Wang and H. Zhao. 2012. Influence of air-knife wiping on coating thickness in hot-dip galvanizing. **J. Iron. Steel Res. Int.** 19(6): 70–78.