APPLICATION OF GREY-TAGUCHI ANALYSIS OPTIMIZATION METHOD FOR THERMAL SPRAY COATINGS

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Abstract

This paper presents the application of the multi-objective optimization method by Grey –Taguchi analysis to study the simultaneous influence of HVOF spray parameters in order to simultaneously improve the properties of the WC-12Co coating on inner cylinder surface of S40C Steel Pipe includes Hardness, adhesion strength, porosity. The spray parameters studied include spray distance (L), powder feed rate (P), relative movement speed between the nozzle and the surface of the substrate (V). The Grey relation coefficients simultaneously represent the investigated coating properties based on experimental results determined and optimized by the Taguchi method. Optimal results determined $L_2P_1V_3$ with L_2= 0.25m, P_1 = 20g/min; V_3 = 0.2 $m.s^{-1}$ is the spray parameter for the largest Grey coefficient (0.79), which is the optimal multi-objective parameter to be determined. The experimental verification that the coating properties were improved simultaneously with: hardness is 1315.2 HV, adhesion strength is 64.5 MPa, coating porosity is 1.51%. The influence of each spray parameter on the coating properties is also studied based on the Gray relation coefficient, which is also determined by ANOVA analysis of variance such as: L is 36.4 %, P is 15.5% , V is 46.6 %, the error effect is not significant with 1.5 %. This study has provided a method to simultaneously improve the efficient output properties including the application of thermal spray technology.

Keyword: HVOF, WC-12Co, Grey analysis, multi-objective optimization

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1. Introduction

The WC-12Co coating by HVOF spray has high hardness and wear resistance due to the high percentage of WC component (88%). The parameters used in the HVOF spraying process can affect the phase transition during the formation of the coating, resulting in changes in the coating's hardness [1, 2]. In addition, the coating's high adhesion strength and low porosity are critical properties that enhance its durability and workability. Hence, improving these properties while maintaining high synthetic mechanical properties can enhance the coating's quality. Furthermore, depositing and forming a coating on the inner cylindrical surface is often more challenging than on the flat outer cylindrical surfaces. Therefore, research to ensure the coating's quality properties on the inner cylinder surface is crucial.

Currently, data processing tools provide effective and reliable solutions for technical requirements. Multi-response methods are the solutions that meet these requirements, as they can evaluate the simultaneous effects of multiple process parameters to achieve the best output criteria.

Many optimization methods have been used by scientists in their research, such as Taguchi, EDM, OEC, surface optimization, and even artificial intelligence-based methods [3, 4,]. However, the Taguchi method has advantages based on experimental design, including fewer experiments required, ease of analysis, and quick determination of optimal spay parameters. The Grey analysis method has also been widely applied by many scientists in their studies [5, 6].

In this study, the Grey optimization method based on L9-Taguchi experimental design [7] was used to conduct experiments. The optimized spray parameters included spray distance (L), spray flow rate (P), and the velocity of movement between the spray nozzle and the surface of the substrate (V), as well as the hardness, adhesion strength and porosity of the WC-12Co coating layer on the inner surface of S40C steel pipe (OD = ; ID =). Analysis of variance (ANOVA) [6] evaluated the influence of these parameters on the Grey coefficient. The Grey coefficients for each experimental result represented the coating properties, which were optimized by the Taguchi method to find the best experimental parameters with the highest predicted Grey coefficient. A second-degree mathematical function based on the Grey coefficients of the experimental results was determined using the least squares method. This mathematical function predicted all Grey coefficient values for all possible experimental parameters that could be designed based on the levels of the studied spray parameters ($3^3 = 27$). The maximum value interpolated from the Grey coefficient mathematical function that matched the optimized results using the Taguchi method affirmed the reliability of the optimization using the Taguchi method and the multi-objective optimization results based on the Grey analysis technique.

2. Experimentation procedue

2.1 Materials

The spraying process was carried out using the HVOF HP-2700M spray device. The coating was deposited on the inner cylindrical surface of tubes made from S40C material with diameters of OD = 406.4 mm and ID = 390.54 mm (Fig.1). WC-12Co powder with a particle size of 15÷45 µm was used for the experimental spraying process with coating thickness of samples in the range 450 ÷ 500 µm

Figure 1. The specimens before spraying (on the left) and after spraying (on the right)

2.2 Experimental Design

The HVOF spraying parameters under investigation were determined at three levels of values: The spraying distance L with L1 = 0.2, L2 = 0.25, L3 = 0.3 m; the spraying flow rate P with P1 = 20, P2 = 26, P3 = 32 g.min-1; relative movement speed between the nozzle and the substrate V with V1 = 0.1, V2 = 0.15, V3 = 0.2 m/s. The experimental parameters were arranged in an orthogonal array L9 - Taguchi (Table 1). Other spraying parameters were fixed at the values shown in Table 2.

Table 1. L9 orthogonal array with the investigated spraying parameters.

Exp. number	Parameters		
	L	P	V
1	0.2	20	0.1
2	0.2	26	0.15
3	0.2	32	0.2
4	0.25	20	0.15

5	0.25	26	0.2
6	0.25	32	0.1
7	0.3	20	0.2
8	0.3	26	0.1
9	0.3	32	0.15

Table 2. Other HVOF spray parameters were used

Parameter	Oxygen pressure (MPa)	Propane pressure (MPa)	Propan flow ($l.min^{-1}$)	Air pressure (MPa)	Air flow ($l.min^{-1}$)	Nitrogen pressure (MPa)	Nitrogen flow ($l.min^{-1}$)
Value	0.98	0.686	40	0.686	550	0.4	20

2. Experiment method

The experimental spraying samples were made from a DN 400 S40C steel pipe, which was cut into sections of 30 mm length. The inner surface of the cylinder was sandblasted using a TSA-206 sandblasting device (Vietnam) with 0.5 mm sand particles to achieve a surface roughness of 10 Ra, as measured by a Mitutoyo SJ-410 roughness tester. After sandblasting, the sample was cleaned of debris using dry compressed air, and WC-12Co coating was sprayed on it for about an hour to prevent the substrate surface from oxidation.
The spraying process was carried out using an HVOF HP-2700M spraying device. The WC-12Co powder used had a composition of 88% WC and 12% Co, as specified in the table... The sample temperature was maintained between 1500C to 2000C during the spraying process. The coating thickness obtained was in the range of 450÷500 (±50) µm.

2.4 Coatings properties characterization evaluation methods
Microhardness, adhesion strength, and porosity are fundamental properties of the coating that are determined. Microhardness is measured using an IndentaMet 1106 microhardness tester (USA) (measuring range HV 0.1) according to ASTM E384-17:2011 [8]. The microhardness value of the sample is the average of five different measurement points in the direction of the coating thickness. The porosity of the coating is calculated on IMJ software based on the microscopic organization image of the coating on the cross-sectional surface with a magnification of 200x [10]. The porosity value is determined as a percentage of the total area of the pores (black color) on the entire area of the image (image...).

Adhesion strength of the coating with the substrate surface is determined based on JIS-H-8666-1980 standard [9]. The coated samples are cut into strips with the dimensions shown in the figure, and the surface of the coating is ground to ensure a coating thickness of 400 µm. The adhesion strength test of the coating with the substrate surface is performed on a tensile-compression testing machine to determine the compressive force P (N). The adhesion stress σa is calculated as the ratio of P to the adhesion area of the coating with the substrate surface A (mm^2): $\sigma_a = P/A$ (MPa).

2.5 Taguchi method
In this study, the Taguchi method was used to design experiments and optimize the parameters of spray L, P, V for the Grey factor and determine the optimal multi-objective parameters. The Taguchi single-objective optimization method was applied in this case because the Grey factors represent the coating properties with the same spray parameters and become the only output criteria. The optimization process is based on determining the S/N values with the quality characteristic "larger is better" (Eq1).
In addition, the single-objective optimized parameters for hardness, adhesion strength with the quality criterion of "the larger, the better", and the coating porosity with the quality criterion of "the smaller, the better" were also determined as a basis for comparison and to demonstrate the advantages of the multi-objective optimized results. The optimization process was performed using Minitab 2018 software.
The S/N ratios for the quality characteristics are as follows:
Larger is better:

$$S/N = -10\log\left(\frac{1}{n}\sum\frac{1}{{y_i}^2}\right) \qquad (1)$$

Small is better:
Where n is the number of experiments conducted and yi is the measured value of the i-th experiment with i = 1, ..., 9.

2.6 Multi-objective optimization method using Grey relational analysis

The Grey method is proposed as a tool to evaluate the influence of various parameters on output properties simultaneously by determining the relationship between outputs using the Grey coefficient. Optimizing multiple output properties becomes a single objective optimization problem, which is the Grey coefficient. The number of experiments is based on the Taguchi experimental design for the influencing parameters. The steps for optimizing Grey are as follows:

Step 1. Data normalization:

Most results of the studied responses have different units, making them not comparable and not combinable with each other. Grey analysis proposes to standardize of data for response variables into corresponding grey coefficients. This allows for the response variables to have the same unit so that they can be compared and combined for further analysis. The standardization values with the quality characteristic of "larger is better" are limited to the range of [0÷1] and are determined by formula (2):

$$x_i(k) = \frac{y_{i(k)} - miny_{i(k)}}{maxy_{i(k)} - miny_{i(k)}} \quad (2)$$

Where: i = 1, 2, 3, ... m and m is the number of experiments in the Taguchi orthogonal array; k = 1, 2, ... n and n is the number of output objectives of the experiment; maxyi(k) is the maximum of $y_i(k)$; minyi(k) is the minimum of $y_i(k)$; $y_i(k)$ is the value after Grey relational analysis.

Step 2: *Determining the Grey relational coefficient* The Grey relational coefficient is based on the normalized data of the output characteristics, which shows the correlation between desired experimental data and actual data. The overall Grey relational coefficient (ξi(k)) is then calculated by averaging the corresponding Grey relational coefficients for each performance characteristic using the following equation:

$$\xi i(k) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{0i}(k) + \xi\Delta_{max}} \quad (3)$$

Where: $\Delta_{oi}(k)$ is the absolute value of the difference between the true normalized value and the ideal value:

$$\Delta_{0i} = |y_{0i}^*(k) - y_i^*(k)| \quad (4)$$

Δ_{min} and Δ_{max} are the minimum and maximum values of the absolute difference (Δ_{oi}) of all comparison series. ξ is the discriminant coefficient, ξ ∈[0,1], its purpose is to weaken the effect of Δmax when it is too large and thus increase the difference significance of the correlation coefficient. ξ is taken such that the sum of these coefficients for each output is 1. In this study ξ for hardness, adhesion strength and porosity were chosen to be 1/3.

Step 3: Calculate the Grey relational grade

After the input data has been converted into Grey relational coefficients, they still represent two different criteria. Therefore, to transform them into a single objective function, the weighted sum of these coefficients needs to be calculated. The weighted sum of the Grey relational coefficients is called the Grey Relational Grade, which is calculated as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{m} \xi_i(k) \quad (5)$$

Where i = 1, 2, 3, 4, ... , (the i-th experiment), ξi(k) is the Grey relational coefficient of response k in the i-th experiment, 1/n is the weight assigned to the priority level of the output parameter, and m is the number of experiments. The optimal level of process parameters is the one with the highest Grey relational value.

Step 4: Determining the multi-objective optimal parameters for the Grey relational coefficient using the Taguchi method

The Grey relational coefficient is optimized using the Taguchi method based on the analysis of the signal-to-noise (S/N) ratio, where a larger quality criterion is better. The optimal parameters for the Grey relational coefficient are the multi-objective optimal parameters that need to be determined.

Step 5: Evaluate the influence of the research parameters on all output characteristics simultaneously.

Step 6: Predict the Grey value:

According to the Taguchi method, the optimal Grey relational coefficient value is predicted based on the optimal levels of the influencing parameters determined by formula (6).

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{o}(\overline{y_i} - y_m) \quad (6)$$

Where γ_m being the average of the sum of all Grey relational coefficients; y_i being the average Grey relational coefficient of the optimal level for each factor; o: process paramater.

3. Results and discussion

3.1 Experimental results

The experimental spray samples were analyzed for the microhardness ($HV_{0.1}$) of the coating using an IndentaMet 1106 device (ASTM E384-17: 2011) [8]. The adhesion strength between the coating and the substrate was determined according to JIS-H-8666-1980 [9], while the porosity of the coating layer was evaluated using ASTM B276-05:2015 standards [10]. The measurements were conducted, and the results are presented in Table 3, serving as a basis for optimization.

Table 4. Results of microhardness, adhesion strength, porosity, and corresponding S/N ratios

Exp. number	Spraying parameters			Measured Results		
	L	**P**	**V**	Hardness (HV0,1)	Adhesion strength (MPa)	Porosity
1	0.200	20	0.10	176.3	2.1	.06
2	0.20	26	0.15	029.7	5.3	.92
3	0.20	32	0.20	150.2	1.2	.62
4	0.25	20	0.15	247.2	9.5	.78
5	0.25	26	0.20	185.5	5.6	.61
6	0.25	32	0.10	200.4	8.3	.62
7	0.30	20	0.20	233.1	3.8	.48
8	0.30	26	0.10	093.6	5.0	.90
9	0.30	32	0.15	083.1	7.5	.63

3.2 Optimization of Spraying Parameters for Coating Properties based on Grey Relational Coefficient

Steps 1-3: Based on the experimental results (Table 4), the output results are normalized into Grey relation coefficients ξi for each output property (adhesion strength, hardness, porosity) and the representative Grey relational grade (γ_i) for all responces, as presented in Table 4 below:

Table 4. Results of Grey analysis from Steps 1-3.

No.	$y^*_i(k)$			$\Delta_{oi}(k)$			$\xi_i(k)$			γ_i	Rank
	ĐC	BD	DX	ĐC	BD	DX	ĐC	BD	DX		
1	0.67	0.10	0.00	0.33	0.90	1.00	0.51	0.27	0.25	0.34	*9*
2	0.00	0.82	0.72	1.00	0.18	0.28	0.25	0.64	0.54	0.48	*2*
3	0.55	0.66	0.28	0.45	0.34	0.72	0.43	0.50	0.32	0.41	*6*
4	1.00	0.54	0.81	0.00	0.46	0.19	1.00	0.42	0.64	0.69	*3*
5	0.72	1.00	0.92	0.28	0.00	0.08	0.54	1.00	0.80	0.78	*1*
6	0.78	0.40	0.28	0.22	0.60	0.72	0.61	0.36	0.32	0.43	*5*
7	0.94	0.00	1.00	0.06	1.00	0.00	0.84	0.25	1.00	0.70	*7*
8	0.29	0.18	0.73	0.71	0.82	0.27	0.32	0.29	0.56	0.39	*8*
9	0.25	0.38	0.91	0.75	0.63	0.09	0.31	0.35	0.78	0.48	*4*

Step 4: Optimizing the results of Gray relational grade (γ_i) according to Taguchi with lager is better quality determined the influence of parameter levels presented in Table 5 and Figure 1 graph. Determination results. $L_2P_1V_3$ (L= 0,25m; P = 20 g.s-1; V2 = 0.15 m.s-1) is a spray parameter that simultaneously improves coatings with: high hardness and adhesion strength; low porosity (Figure 2).

Table 5. Level of influence of spray parameters on relation coefficient Grey

Level	1	2	3	Max-min	Rank
L	-7.794	-4.271	-5.929	3.522	2
P	-5.255	-5.581	-7.158	1.903	3
V	-8.308	-5.361	-4.325	3.983	1

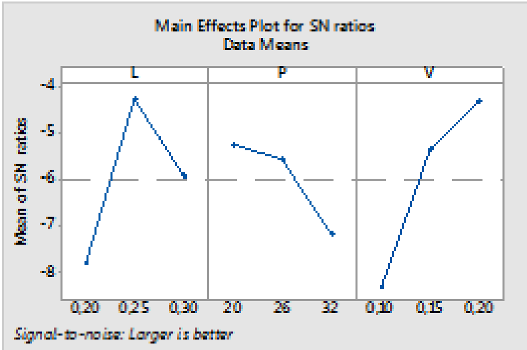

Figure 2. Optimal level chart of the spraying parameters for the Grey relational coefficient.

4. *ANOVA analysis:* The influence of spraying parameters on the Grey coefficient was analyzed using ANOVA, and the results showed that V (46.6%) > L (36.4%) > P (15.5%), with a small error is 1.5%. The P-values < 0.05 indicate the significance of the selected spraying parameters in this study.

Table 6. Results of variance analysis based on the Grey relational grades

Source	DF	Adj SS	Adj MS	F-Value	P-Value	ffect %)
L	2	0.072311	0.036155	24.78	0.039	6.4%
P	2	0.030888	0.015444	10.59	0.086	5.5%
V	2	0.092520	0.046260	31.71	0.031	6.6%
Error	2	0.002918	0.001459			.5%
Total	8	0.198637				

Step 6: Determine the optimal Grey relational grade value: According to formula (6), the maximum Grey relational grade corresponding to the $L_2P_1V_3$ spay parameter is 0.79. The optimal Grey relational grade value is higher than the other values in the experiment (range 0.34 to 0.78) (Table 4). These results indicate a 1.7% improvement in the Grey relational grade coefficient.

3.3 Verification of optimal results

The mathematical function determines the value of Grey relational coefficient (γ_i) based on the spray parameters established from the data in Table 4, which serves as the basis for confirming that the optimal Grey relation coefficient has been determined as the best:

$$GRA = -0,0051.A^2 - 0,0051.B^2 - 0,1754.C^2 + 0,2355.A.B - 1,2439.B.C - 0,0128.A.C + 0,3115.A - 0,9006.B + 2,6308.C - 10,7197 \quad (7)$$

The determination coefficient R^2=0.97 and the adjusted determination coefficient R^2_{adj}=0.91 indicate the reliability of the function in the mechanical engineering field. This is also reflected in the comparison chart between the GRA value obtained from experimental results and predicted results, as they are almost identical to each other (Figure 3).

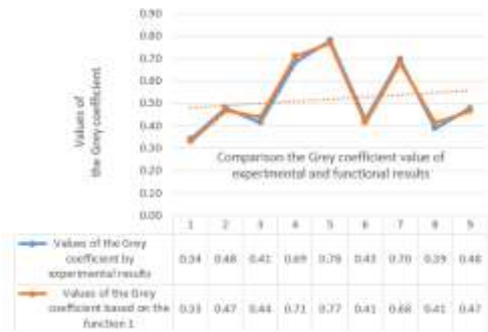

Figure 3. Relationship between Gray relational grade from experiment and prediction of function 7

Moreover, the Grey relational grades for all spay parameters set from the studied levels (3^3=27 cases - Table 7) were determined and presented in the chart in Figure 4. The predicted Grey relational grades have a range of 0.19-0.79, indicating an improvement in the research results. The optimized parameter $L_2P_1V_3$ was determined to be reliable.

Table 7 Shows the 27 spay parameters set from the levels of the studied parameters.

Exp. number	L	P	V	γ_i
1	0.2	20	0.1	0.33
2	0.2	20	0.15	0.49
3	0.2	20	0.2	0.57
4	0.25	20	0.1	0.55
5	0.25	20	0.15	0.71
6	0.25	20	0.2	0.79
7	0.3	20	0.1	0.44
8	0.3	20	0.15	0.60
9	0.3	20	0.2	0.68
10	0.2	26	0.1	0.30
11	0.2	26	0.15	0.47
12	0.2	26	0.2	0.55
13	0.25	26	0.1	0.52
14	0.25	26	0.15	0.69
15	0.25	26	0.2	0.77
16	0.3	26	0.1	0.41
17	0.3	26	0.15	0.58
18	0.3	26	0.2	0.66
19	0.2	32	0.1	0.19
20	0.2	32	0.15	0.36
21	0.2	32	0.2	0.44
22	0.25	32	0.1	0.41
23	0.25	32	0.15	0.58
24	0.25	32	0.2	0.66
25	0.3	32	0.1	0.30
26	0.3	32	0.15	0.47
27	0.3	32	0.2	0.55

Figure 4. Histogram showing the predicted Gray relational grades for all established experimental parameters

The experimental verification with the optimized spray parameters $L_2P_1V_3$ for the coating yielded the following results: hardness of 1315.2 HV, adhesion strength of 64.5 MPa, and porosity of 1.51%, which, when compared to the results in table 9, indicates a significant improvement in the coating properties, while the other spay parameters could not improve all three coating properties simultaneously.

4. Conclusion

This study optimized the determination of optimal spraying parameters for the WC-12Co coating on the inner surface of S40C Steel Pipe by HVOF spraying. Grey analysis and Taguchi method with L9 orthogonal array were experimentally conducted to determine the results as follows:

The Grey analysis method based on Grey correlation coefficient is an effective tool to determine the optimal multi-objective response parameters for multiple outputs simultaneously, even if the outputs are not of the same nature.

This study determined the spraying parameters of $L_2P_1V_3$ (L = 0.25 m; P = 20 g/min; V = 0.2 m/s) that simultaneously improved the high hardness and high adhesion strength with low porosity of the WC-12Co coating on the inner surface of S40C Steel Pipe, with a hardness of 1315.2 HV and an adhesion strength of 64.5 MPa and porosity of 1.51 %.

The influence of each spraying parameter on the coating properties was determined simultaneously through the analysis of variance of the Grey correlation coefficient with V (46.6%) > L (36.4%) > P (15.5%).

The relationship between the spraying parameters and the Grey correlation coefficient was determined by a mathematical function with high reliability of experimental results, confirming that the Grey analysis method based on Taguchi is a quick and effective tool for multi-objective optimization problems.

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