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ORIGINAL ARTICLE

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A robust design in hardfacing using a plasma transfer arc

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Abstract This paper presents the use of the Taguchi-regression method in developing the optimal plasma transferred arc welding (PTAW) process for obtaining high hardfacing quality characteristics. An "optimal" process means that the best performance characteristic would be produced while the least number of process parameters are involved. In the experimental tests, the surface hardening process is conducted using Cobalt-based and Nickel-based powdery metal materials together with L_{18} orthogonal arrays. The dependent variable, wear, obeys the-smaller-the-better quality characteristic, and the performance statistics, the signal-to-noise ratios (SNRs), are obtainable.

The experimental results show that the most efficient process parameters based on analysis of variance are set as follows: hardfacing material, the accelerating voltage, the powder feed rate , and the pre-heat treatment temperature. They account for almost 90% of the total variance of wear. Under the optimal setting, the average error rates for using Taguchi and Taguchi-regression methods are 7.05 and 5.50%, respectively. The outcome of the experiment indicates that predicted values of the optimal setting fit well with the actual data. The reproducibility of the optimal plasma transfer arc hardfacing is obtained from the experimental data of the confirmation run. A reliable analysis based on the results from plasma transfer arc hardfacing conditions can be achieved through the Taguchi-regression method.

Keywords Hardfacing · Multiple linear regression · Plasma transfer arc welding (PTAW) · Taguchi methods

1 Introduction

The plasma transfer arc (PTA) is a unique tool in the hardfacing process and has enormous applications in industry [1, 2]. PTA hardfacing can be efficiently used in almost all metals that are resistant to wear, such as roll surface, extruder screws, knife edges, hammer mills, tractor treads, and bucket teeth. It is also suitable for any hardfacing application that requires minimal defect and dilution during the heating surface hardening process. On the other hand, arc welding methods such as shielded metal arc, flux core arc, and submerged arc [3, 4] are the most frequent heating surface hardening processes used in industry. These methods utilize flexible processes with low cost, but their high thickness of hard surfacing, high dilution, and poor control in melting, to some extent limit their applications.

Wear, existing normally in the form of gradual material removal, is an essential damage of a solid surface by relative motion with either a contacting substance or substances. It commonly occurs on the industrial parts such as gear teeth, cams, shafts, bearings, automotive clutch plates, tools, as well as dies. A plasma transfer arc welding (PTAW) hardfacing process is a thick localized hardfacing heat treatment that is particularly useful for enhancing their surface resistance to wear.

Surface hardening materials have been involved in a number of industrial applications, including local surfacing hard parts that are subject to metal-to-metal sliding high contact stresses and combined with corrosion and oxidation. However, it is not an easy task to surface harden these materials using heat surface hardening processes. Many researchers have conducted using diverse approaches [5–7], for example, Ishida investigated the local melting cast iron with a stationary plasma arc; Kelly [4] reported mechanical properties of cast iron when welded within the

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melted zone by filler metals. It is worth pointing out that most of the studies mainly focus on the mechanical property analysis of the treated zones, but lack the process optimization.

To evaluate process performances more efficiently, Taguchi proposed a methodology that provides a simple, effective, and systematic technique to optimize process designs with better performance, high quality, and low cost. His work provided a fast development in many fields since the 1980s. Much work in optimization studies can be found in mechanical and electrical fields, but few are published in welding engineering [8–10].

Multiple regression analysis is one of the most frequently used statistical techniques, which allow one to model an appropriate functional relationship between the response and the explanatory variables, as well as provide reasonable predictions of the response. Therefore, in this paper, we apply multiple regression analysis to investigate the outcome for PTA surface hardfacing using Taguchi methods. The goals for this article are to not only to present the effect of process parameters, but also develop a most effective hardfacing process using the ideas proposed.

2 PTAW hardfacing hardened processes

2.1 Plasma transfer arc welding (PTAW)

Plasma is typically a type of a gas that is heated to an extremely high temperature and then ionized so that it becomes electrically conductive. The plasma arc welding process uses this plasma to transfer an electric arc to a workpiece. The metal to be welded is first melted by the powerful heat of the arc and then fuses together. In the plasma welding torch, a Tungsten electrode is located within a copper nozzle having a small opening at the tip. A pilot arc, which is transferred to the metal to be welded, is initiated between the torch electrode and nozzle tip. By forcing the plasma gas and arc through a constricted orifice, the torch has a powerful capability in penetration and delivers a high concentration of heat to a local area. Through the arc connecting the plasma gun and the work, PTAW generates a plasma flame whose role is to melt filler metals during the welding or hardfacing processes. Due to the low-power welding torch and shielding used in the PTAW process, argon gas generates a lower speed plasma arc and powdered filler metal by inserting gas through a constricted arc zone and creating a complicated molten hardfacing surface. In addition, the come-and-go oscillation of PTAW for hardfacing is better than automatic gas tungsten arc welding (GTAW) with smooth, accurate weld profiles. In this study, the heating source for PTAW hardfacing experiments originates from the Nittetsu plasma transfer arc machining equipment and the process takes place in a steady powder supply granularity at the degree between 53and 150 µm. From Fig. 1, it shows that the basic PTAW equipment includes a power supply for the arc, non-consumable tungsten electrode for the center, a plasma gas supply with controls, a shielding gas with controls, a water cooling system for the torch, and other controls to assemble all these objects. However, by programming with PTAW, the most wanted production such as engine valves, screws, and guide rollers will be able to produce any desired hardfacing patterns in the work.

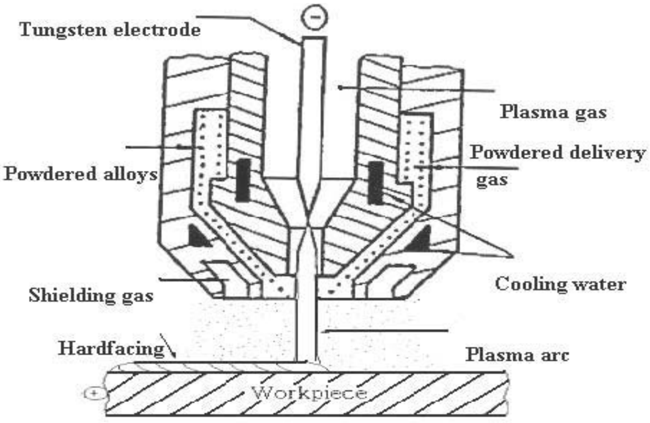

Fig. 1. The plasma transfer arc welding system

2.2 Experimental materials and their characteristics

The hardfacing materials studied are the cobalt-based and the nickel-based powered alloys that consist of Stellite #1 and Colmonoy #5 in the powder metal. Tables 1 and 2 present the experimental layout of the hardfacing control parameters obtained using the L_{18} orthogonal array, and their corresponding levels. The annealing 45C carbon steel in the substrate matrix consists of C (0.48%), Si (0.22%), Mn (0.71%), P (0.013%) and S (0.008%). The dimensions of the specimens are $12 \times 50 \times 200\,\text{mm}^3$. PTA hardfacing is performed using Nittetsu PTA machining equipment.

In this study, we use sliding wear testers with a pin on disc type to measure the wear weight loss. The American Society for Testing and Materials (ASTM) refers the sliding wear

Table 1. Control factors and levels for L_{18} array

Symbol	Control factor	Level 1	Level 2	Level 3
A	Hardfacing material	Stellite # (1.3 wt% C)	Colmonoy #5 (2.0 wt% C)	
B	Accelerating voltage (V)	20	23	26
C	Electrical current (A)	150	170	190
D	Powder feed rate (g/min)	15	25	35
E	Waving oscillation (Hz)	150	300	450
F	Plasma gas rate (l/min)	1.3	1.8	2.5
G	Rotation (rpm)	0.35	0.55	0.75
H	Pre-heat treatment (°C)	25	150	250

Table 2. Taguchi experimental results

No. of test	Control factor and level A	B	C	D	E	F	G	H	Wear weight loss (g) Trial 1	Trial 2	Quality characteristic signal-to-noise ratio (SNR)
1(*)	1	1	1	1	1	1	1	1	0.0100	0.0123	39.009
2	1	1	2	2	2	2	2	2	0.0094	0.0085	40.953
3	1	1	3	3	3	3	3	3	0.0182	0.0205	34.251
4	1	2	1	1	2	2	3	3	0.0239	0.0256	32.123
5	1	2	2	2	3	3	1	1	0.0121	0.0132	37.950
6	1	2	3	3	1	1	2	2	0.0172	0.0168	35.390
7	1	3	1	2	1	3	2	3	0.0306	0.0324	30.030
8	1	3	2	3	2	1	3	1	0.0151	0.0182	35.534
9	1	3	3	1	3	2	1	2	0.0288	0.0310	30.481
10	2	1	1	3	3	2	2	1	0.0281	0.0298	30.763
11	2	1	2	1	1	3	3	2	0.0168	0.0148	36.010
12	2	1	3	2	2	1	1	3	0.0345	0.0257	30.337
13	2	2	1	2	3	1	3	2	0.0287	0.0324	30.284
14	2	2	2	3	1	2	1	3	0.0341	0.0298	29.891
15	2	2	3	1	2	3	2	1	0.0108	0.0152	37.599
16	2	3	1	3	2	3	1	2	0.0321	0.0352	29.451
17	2	3	2	1	3	1	2	3	0.0185	0.0168	35.055
18	2	3	3	2	1	2	3	1	0.0256	0.0281	31.412

(*): Initial test setting

testers as the standard in controlling experimental conditions, which include contact forces, sliding line speeds and wear sliding distances. The quality characteristic concerned here is the wear resistance of hardfacing-treated specimens and wear weight losses can assess it through wear tests. In general, a lower wear weight loss usually implies a better wear resistance. We perform these wear tests under conditions as follows: loading of 10 kgw, sliding speed at 1.04 m/s, a sliding distance of 500 m, and no lubricates.

2.3 PTAW hardfacing hardened properties

Hardfacing is the procedure that deposits alloys on metallic parts through welding and forms protective surface, which resists abrasion with impact, heat, corrosion, or combinations of these factors. Understanding some fundamental principles in metallurgy will help one to set up intelligent hardfacing procedures. The wear resistances of a hardfacing deposit depend on two variables which are the analysis and cooling rate of the deposit. In this paper, we focus on analyzing a series of deposits during the welding or hardfacing processes and finding the most appropriate parameters to enhance the chance of better performance quality. As for the importance of the deposits' cooling rates, we will discuss it in future research.

3 Taguchi-regression for PTAW hardfacing

3.1 Experimental design using orthogonal arrays

The purpose of this experimental design is to optimize the PTAW hardfacing factors in addition to produce high hardfacing quality. To be precise, we will apply parameter design in statistics to find the best combination of control factors. Moreover, making use of Taguchi orthogonal arrays allows one to reduce the number of necessary experimental tests. Since the orthogonal arrays are self-balanced and mutual-balanced in experimental designs, one can obtain sufficient information with only fractional factorial experiment. In addition, based on its good even distribution of factorial interactions over control factors, we employ a L_{18} array in the experimental tests.

The choices for these control factors (A-H in Table 1) in the PTAW hardfacing process are based on opinions from welding experts and the controllability of welding equipments. We select these levels for the propriety and perform 18 Taguchi experiments.

3.2 Multiple linear regression model and estimates

The multiple regression analysis is a procedure that predicts a single dependent variable by two or more independent variables through a linear function. That is to say, the dependent variable Y can be predicted by a linear regression function of k independent variables $X_1, X_2, \ldots, X_k$. Specifically, with a sample of n observations of the dependent variable Y, the regression model can be expressed as:

$$Y_i = \beta_0 + \sum_{j=1}^{k} \beta_j X_{ij} + \varepsilon_i, \quad i = 1, 2, \ldots, n \tag{1}$$

where Y_i stands for the ith observation of Y, X_{ij} denotes the ith observation of the jth independent variable, and $\beta_0, \beta_1, \ldots, \beta_k$ are the unknown regression parameters to be determined. The random errors ε_i's are assumed to be independent of each other, and follow the normal distribution with a mean of zero and a constant variance of σ^2. Hence, the mean of Y_i is:

$$E(Y_i) = \beta_0 + \sum_{j=1}^{k} \beta_j X_{ij}, \quad i = 1, 2, \ldots, n. \tag{2}$$

Express Eq. 1 in the matrix form and yield

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}$$

where

$$\mathbf{Y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, \mathbf{X} = \begin{bmatrix} 1\ x_{11} \ldots x_{1k} \\ 1\ x_{21} \ldots x_{2k} \\ \vdots\ \ \vdots\ \ldots\ \vdots \\ 1\ x_{n1} \ldots x_{nk} \end{bmatrix}, \boldsymbol{\beta} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{bmatrix}, \boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix}.$$

In addition, the mean of **Y** is:

$$E(\mathbf{Y}) = \mathbf{X}\boldsymbol{\beta}.$$

To obtain the best prediction for **Y**, we apply the least squares criterion to determine the value of the regression parameter $\boldsymbol{\beta}$. The least-squares estimate of the vector $\boldsymbol{\beta}$, represented by $\hat{\boldsymbol{\beta}}$, allows predicted values to be fairly close to observed values, and minimizes the sum of squares of errors (SSE), which takes the form:

$$SSE = \sum_{i=1}^{n} [Y_i - E(Y_i)]^2 = (\mathbf{Y} - \mathbf{X}\boldsymbol{\beta})^T (\mathbf{Y} - \mathbf{X}\boldsymbol{\beta}). \qquad (3)$$

Apply techniques in matrix algebra to minimize Eq. 3 and yield:

$$\hat{\boldsymbol{\beta}} = \begin{bmatrix} \hat{\beta}_0 \\ \hat{\beta}_1 \\ \vdots \\ \hat{\beta}_k \end{bmatrix} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y} \qquad (4)$$

provided that the matrix $\mathbf{X}^T\mathbf{X}$ is non-singular. Therefore, $\hat{Y}_i$, denoting the predicted value of Y_i, is evaluated as:

$$\hat{Y}_i = \hat{\beta}_0 + \sum_{j=1}^{k} \hat{\beta}_j X_{ij}. \qquad (5)$$

3.3 Evaluation of signal-to-noise ratio (SNR)

Taguchi has extended the audio concept of signal-to-noise to a multivariable experimentation. The SNR formula is designed in a way such that one can select the greatest value as the optimizing experimental results. However, the technique for calculating SNR varies since it depends on whether a large, small, or on target response is in question. In the PTAW hardfacing process, we want the non-negative wear weight loss to be as small as possible; therefore, a SNR formula for the-smaller-the-better response is desirable. Taguchi's SNR formula, which takes both the average and the standard deviation into consideration, is derived as:

$$SNR_i = -10 \log \left[\frac{1}{r} \left(\sum_{j=1}^{r} Y_{ij}^2 \right) \right], \qquad (6)$$

where SNR_i represents the SNR of the ith test, Y_{ij} stands for the observed wear weight losses of the jth trial under the ith test, and r is the total number of trials under each test. In this study, we perform two repeated trials in each of the 18 hardfacing tests; therefore, $r = 2$ and i ranges from 1 to 18. As the predicted wear weight loss for the Taguchi-regression method possesses the-smaller-the-better property, the SNR for this method can be evaluated by replacing Y_{ij} with $\hat{Y}_{ij}$, which stands for the predicted wear weight loss of the jth repeated trial under the ith test obtained from the regression equations.

3.4 Analysis of variance (ANOVA)

Since we are interested in testing the effects of the control factors on the response variable, wear weight loss, the ANOVA is the technique required to perform the analysis. The goal of the ANOVA is to estimate and test the effects of different treatments on the response variables. From the analysis, we are able to identify the most important factors in terms of the quality characteristics. The ANOVA table consists of variations (sums of squares) due to factors and random errors, degrees of freedom, mean squares, and F ratios. The total variation, or the sum of squares (*SST*) of SNRs and its degrees of freedom (DOF_{Total}) are:

$$SST = \sum_{i=1}^{n} (SNR_i - \bar{S}\bar{N}\bar{R})^2, \quad DOF_{\text{Total}} = n - 1, \qquad (7)$$

where SNR_i represents the SNR of the ith test, $\bar{S}\bar{N}\bar{R}$ represents the overall mean of SNRs, and n is the number of experimental tests. The *SST* of SNR ratios can be partitioned into the sum of squares from each factor and the sum of squares for errors (*SSE*). For the Jth control factor, the sum of squares, SS_J, and the corresponding degrees of freedom, DOF_J, are:

$$SS_J = n_J \sum_{k=1}^{l_J} (\bar{S}\bar{N}\bar{R}_{Jk} - \bar{S}\bar{N}\bar{R})^2, \quad DOF_J = l_J - 1, J = 1, \ldots m, \qquad (8)$$

where the $\bar{S}\bar{N}\bar{R}_{Jk}$ is the mean of the SNRs of the Jth factor measured at the kth level, l_J is the number of levels of the Jth factor, n_J is the total number of tests run at each level of the Jth factor, and m is the number the factors. To be specific, in our study, we have,

$$n_1 = 9, n_2 = \cdots = n_8 = 6 \quad \text{and} \quad l_1 = 2, l_2 = \cdots = l_8 = 3.$$

The mean square for the Jth factor (MS_J) represents the ratio of SS_J to DOF_J. The mean square error (MSE) is the unbiased estimator for the variance of random errors, and represents the ratio of *SSE* to its corresponding degrees of freedom. Furthermore, the F-value, which corresponds to the ratio of the MS_J to the MSE, determines whether the Jth factor is significant.

4 Experimental results and discussion

4.1 Analysis of the experimental results

The interested quality characteristic of the PTAW hardfacing process in this study is the local wear of the hardfacing zone. Table 2 displays a complete experimental layout and their resultant data. Note that, in each of the tests, we carry out two repetitive trials. We use the data from the 18 various experimental tests and eight independent variables to predict the minimum local wear weight losses via the multiple regression model. According to the procedures mentioned in 3.2, we first solve the parameter vector $\hat{\beta}$ and then use it to obtain the predicted wear weight losses. Using data from the 1st trial, the vector Y, the matrix X, and the vector $\hat{\beta}$ are

$$Y=\begin{bmatrix}0.010\\0.0094\\0.0182\\\vdots\\0.0185\\0.0256\end{bmatrix}_{18\times1},\quad X=\begin{bmatrix}1 & 1.3 & 20 & 150 & \ldots & 0.35 & 25\\1 & 1.3 & 23 & 150 & \ldots & 0.55 & 150\\1 & 1.3 & 26 & 150 & \ldots & 0.75 & 250\\\vdots & \vdots & \vdots & \vdots & \ldots & \vdots & \vdots\\1 & 2.0 & 23 & 190 & \ldots & 0.55 & 250\\1 & 2.0 & 26 & 190 & \ldots & 0.75 & 25\end{bmatrix}_{18\times9}$$

$$\hat{\beta}=\begin{bmatrix}\hat{\beta}_0\\\hat{\beta}_1\\\hat{\beta}_2\\\vdots\\\hat{\beta}_7\\\hat{\beta}_8\end{bmatrix}_{9\times1} \tag{9}$$

Use Eq. 4 and yield:

$$\hat{\beta}=(X^TX)^{-1}X^TY=\begin{bmatrix}-0.0136\\0.010143\\-0.00051\\0.00014\\0.0003\\0.0000000556\\-0.00089\\-0.00971\\0.000043\end{bmatrix}_{9\times1} \tag{10}$$

Thus, according to the observations of trial 1, the best predicted wear weight $\hat{Y}$ of the PTAW hardfacing with the given values of control variables: $X_1=x_1,\ldots,X_8=x_8$, is:

$$\begin{aligned}\hat{Y}=&-0.0136+0.010143X_1-0.00051X_2+0.00014X_3\\&+0.0003X_4+0.0000000556X_5-0.00089X_6\\&-0.00971X_7+0.000043X_8\end{aligned} \tag{11}$$

Similarly, the best predicted wear weight loss $\hat{Y}$ from trial 2 can be also obtained. Table 3 shows the estimated parameter vector $\hat{\beta}$ in the regression equations for both trials.

Table 3. Regression parameter estimates

Control factor	Estimated parameter Trial 1	 Trial 2
Intercept	−0.0136	−0.01864
Hardfacing material (A)	0.010143	0.007825
Accelerating voltage (B)	−0.00051	−0.000844
Electrical current (C)	0.000140	0.000209
Powder feed rate (D)	0.000300	0.000288
Waving oscillation (E)	5.56E-08	5.28E-06
Plasma gas rate (F)	−0.00089	0.000854
Rotation (G)	−0.00970	0.003166
Pre-heat temperature (H)	0.000042	0.000025

4.2 Multiple linear regression analysis of PTAW hardfacing process

In this research, we use all the control factors as independent variables in generating a multiple linear regression model. Predicted wear weight losses yielded from the least-squares regression equations for both trials, and the SNRs of the 18 tests, are in Table 4. The respective coefficients of determination, R^2, are 0.79 and 0.74 for trials 1 and 2, which indicate that over 70% of the variation of wear is accounted for by the corresponding regression equations.

4.3 Estimated SNR effects for the quality characteristic

We evaluate the performances of each experimental test by its corresponding SNR using Eq. 6. Tables 2 and 4 provide the yielded SNRs using the Taguchi method and the Taguchi-regression method, respectively. Furthermore, the response table of the SNRs obtained from the Taguchi-regression method and the graphical representation of the response effects are shown in Table 5 and Fig. 2. It is easy to see the effects of control factors and their levels from the SNRs. The range of the level-SNRs within each factor implies the significance of the factor. The larger the range, the more important the factor is. Therefore, we can identify H (pre-heat temperature) as the most significant factor for the process robustness, followed by factors D (powder feed rate), B (accelerating voltage), and A (hardfacing material). They have relatively great impacts on the variability in wear. Table 5 and Fig. 2 also suggest that, for the Taguchi-regression method, the best levels for each control factor are A1, B1, C3, D1, E1, F3, G3 and H1 since they have the highest SNRs within these factors. To summarize, the best experimental treatment is set as follows: cobalt-based, accelerating voltage at 20 V, electric current at 190 A, the rate of powder feed at 15 g/min, waving oscillation at 150 Hz, the rate of plasma gas at 2.5 l/min, the speed of rotation at 0.75 rpm, and pre-heat temperature at 25 °C.

4.4 Prediction of the optimized PTAW hardfacing process

Predictions of the SNRs can be made based on the data from the regular Taguchi method and the Taguchi-regression method. Upon identifying the optimal settings for both methods, we can

Table 4. Taguchi-regression experimental results

Test	Control factor and level A	B	C	D	E	F	G	H	Regression predicted Y Trial 1	Trial 2	Quality characteristics Mean	S. D.	SNR(db)
1(*)	1	1	1	1	1	1	1	1	0.0115	0.0117	0.01161	0.00014	38.70464
2	1	1	2	2	2	2	2	2	0.0160	0.0158	0.01589	0.00012	35.97497
3	1	1	3	3	3	3	3	3	0.0192	0.0194	0.01932	0.00018	34.27796
4	1	2	1	1	2	2	3	3	0.0197	0.0215	0.02060	0.00132	33.70365
5	1	2	2	2	3	3	1	1	0.0147	0.0188	0.01679	0.00290	35.37118
6	1	2	3	3	1	1	2	2	0.0207	0.0191	0.01991	0.00111	34.00611
7	1	3	1	2	1	3	2	3	0.0268	0.0290	0.02791	0.00159	31.07042
8	1	3	2	3	2	1	3	1	0.0177	0.0228	0.02027	0.00360	33.72794
9	1	3	3	1	3	2	1	2	0.0190	0.0202	0.01959	0.00082	34.14991
10	2	1	1	3	3	2	2	1	0.0222	0.0243	0.02328	0.00148	32.64164
11	2	1	2	1	1	3	3	2	0.0175	0.0176	0.01754	0.00005	35.11867
12	2	1	3	2	2	1	1	3	0.0282	0.0215	0.02487	0.00476	31.93094
13	2	2	1	2	3	1	3	2	0.0259	0.0277	0.02683	0.00128	31.41919
14	2	2	2	3	1	2	1	3	0.0351	0.0307	0.03292	0.00310	29.61218
15	2	2	3	1	2	3	2	1	0.0154	0.0175	0.01642	0.00150	35.65638
16	2	3	1	3	2	3	1	2	0.0345	0.0363	0.03541	0.00124	29.01162
17	2	3	2	1	3	1	2	3	0.0304	0.0297	0.03005	0.00056	30.44149
18	2	3	3	2	1	2	3	1	0.0198	0.0225	0.02118	0.00189	33.44756

(*): Initial test setting

Table 5. The response table of SNRs for the Taguchi-regression method

	A	B	C	D	E	F	G	H
Level 1	34,55	34,77	32,76	34,63	33,66	33,37	33,13	34,92
Level 2	32,14	33,29	33,37	33,20	33,33	33,25	33,30	33,28
Level 3	N/A	31,97	33,91	32,21	33,05	33,42	33,62	31,84
Effect	2,41	2,80	1,15	2,42	0,61	0,16	0,49	3,09

estimate their SNRs through the additivity law of the linearity of the PTAW hardfacing process. Hence, the formula is as follows:

$$SNR_{\text{Optimal}} = \bar{S}\bar{N}\bar{R} + \sum_{J=1}^{m} (SNR_J - \bar{S}\bar{N}\bar{R}) \tag{12}$$

where SNR_{Optimal} is the estimated SNR of the optimal setting, SNR_J is the highest level-SNR of the jth factor, $\bar{S}\bar{N}\bar{R}$ is the overall average of SNRs, and m is the number of factors. Based on Eq. 5, the predicted SNRs for the optimal settings from both the Taguchi method and the Taguchi-regression method are 44.3200 and 41.5204, respectively.

4.5 Verification experiments

The confirmation experiments for the optimal settings using both methods are performed for the verification purpose. We also use test 1 as the initial test to compare with the optimal tests for both methods. The experimental results and comparisons with the predicted SNRs are listed in Tables 6 and 7. Experimental results show that the actual gain of SNR is 2.1347 db in the Taguchi method and 3.9858 db in the Taguchi-regression method. They also show that the latter method produces an SNR that is closer to the prediction. Undoubtedly, the Taguchi-regression method is superior to the Taguchi method since it yields higher SNRs, which is equivalent to meaning better quality. These predicted gains not only confirm excellent additive or reproducibility but also provides us sufficient confidence in the factorial effects we select as important. It is clear in Table 7 that the optimal setting in wear weight loss by the Taguchi-regression method approach the confirmation run better than the Taguchi method. In addition, Taguchi-regression method results in the lower standard deviations for the whole tests, which indicates a significant improvement in the process robustness. Furthermore, the results of confirmation runs of the optimal tests for both methods are given in Table 6. The SNR of the confirmation run of the optimal setting from the Taguchi method is 41.1432 db, while the SNR is 42.6904 db from the Taguchi-regression method, which is the largest among all the experiments. The corresponding average weight loss from the optimal setting is 0.00734 g, which is the lowest and actually is much lower than the initial setting.

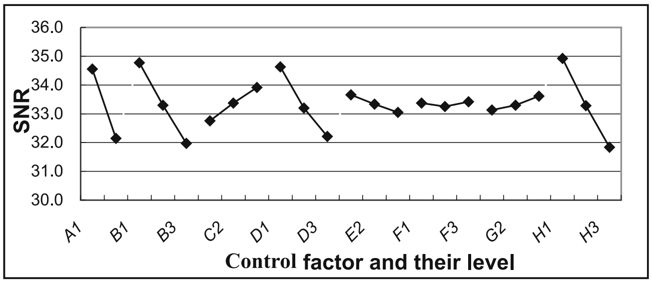

Fig. 2. The SNR response graph for the Taguchi-regression method

4.6 ANOVA using Taguchi-regression method

We evaluate the effects of control factors in the PTAW hardfacing process based on information from ANOVA, which is useful

Table 6. Verification experiments

Test	Control factors and level								Quality characteristics				Confirmation
	A	B	C	D	E	F	G	H	Trial 1	Trial 2	Mean	S. D.	SNR (db)
Optimal Taguchi setting	1	1	2	1	2	1	2	1	0.0089	0.0086	0.0087	0.0002474	41.1432
Optimal Taguchi regression setting	1	1	3	1	1	3	3	1	0.0065	0.0072	0.0073	0.0001770	42.6904

Table 7. Comparisons between the initial test and the optimal test

Test	Taguchi-regression prediction (db)	Taguchi prediction (db)	Taguchi-regression confirmation (db)	Taguchi confirmation (db)
Initial setting	38.3813	39.8561	38.7046	39.0085
Optimal setting	41.5204	44.3200	42.6904	41.1432
Gain	3.2191	4.4639	3.9858	2.1347

to identify the important factors for the quality characteristic. Therefore, we can control those selected factors more carefully during the process so to make sure stable and high quality products can be produced.

The ANOVA results for the Taguchi-regression are shown in Table 8. We can identify that factors H, A, B, and D are the most significant processing parameters, in descending importance order. Their individual contribution percentages are well above 15% and the whole accounts for about 90% of the total variance. Clearly, conclusions drawn from the ANOVA coincide with those reflected in Table 5 and Fig. 2.

4.7 Comparisons between Taguchi and Taguchi-regression methods

In order to obtain a fair and systematical comparison between the Taguchi and Taguchi-regression methods, we use the same settings for each process factors in the experimental tests and check the wear loss using both methods. The predictions and comparisons to the actual wear loss shown in Figures 3 and 4 both indicate that predicted and actual values are quite close using both methods, which implies that they both provide satisfactory predictions. However, with a closer inspection, we can find that the Taguchi-regression provides a better fit than the Taguchi method. Figure 5 plots the error percentages between the predicted and the actual data for both methods used for the experi-

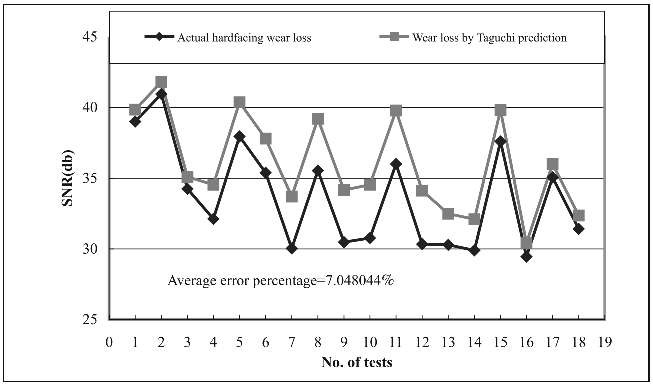

Fig. 3. Comparison between Taguchi predictions and actual values

Table 8. ANOVA table for the Taguchi-regression method

Source of variation	Sum of squares	Degrees of freedom	Mean of squares	F ratio	Pure sum of square	Percentage contribution
A	26.1777	1	26.1777	50.303	25.6573	24.9108
B	23.5453	2	11.7727	22.622	22.5045	21.8498
C	3.9941	2	1.9970	3.838	2.9533	2.8674
D	17.7055	2	8.8527	17.011	16.6647	16.1799
E	1.1169	2	0.5585	1.073	0.0761	0.0739
F	0.0844	2	0.0422	0.081	−0.9564	−0.9285
G	0.7300	2	0.3650	0.701	−0.3108	−0.3017
H	28.6017	2	14.3008	27.481	27.5609	26.7591
Error	1.0408	2	0.5204	1.000		8.5894
Total	102.9964	17				100

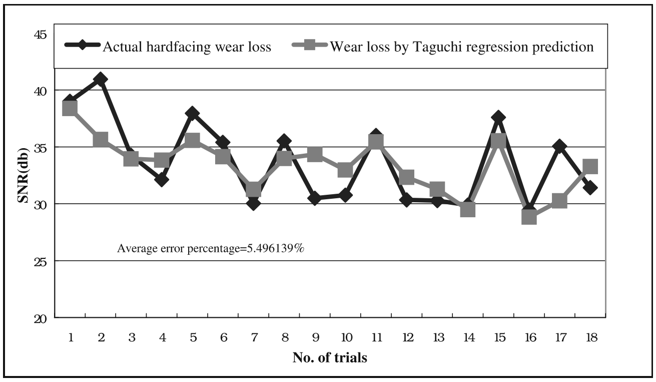

Fig. 4. Comparison between Taguchi Regression predictions and actual values

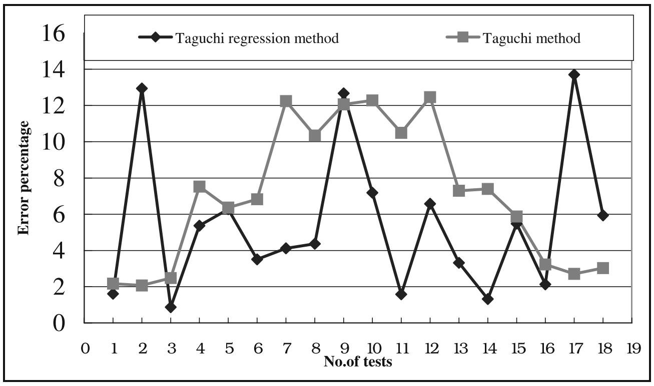

Fig. 5. Error percentages for Taguchi and Taguchi-regression methods

ments. It is quite clear that the Taguchi-regression method generates less error in predicting wear weight losses than the Taguchi method in most tests. To be more precise, the average error of the prediction is 5.50% in Taguchi-regression and 7.05% in the Taguchi method. Therefore, the Taguchi-Regression method is a more accurate technique for predicting the wear loss in PTAW hardfacing.

5 Conclusions

This article presents the use of the Taguchi-regression in developing a robust, high speed, and high quality PTAW hardfacing process. Through proper system model simulations, quality characteristics in the hardfacing process can be optimized. Comparing the experimental results between the Taguchi and the Taguchi-regression methods, we have the following conclusions:

1. The most important factors that affect the wear weight loss are the hardfacing materials, accelerating voltages, powder feed rates, and pre-heat treatments. These factors account for about 90% of the total variance.
2. For both methods, the following settings are predicted to yield the best result:
   For the Taguchi method:
   Factor A – level 1, Factor B – level 1, Factor C – level 2, Factor D – level 1,
   Factor E – level 2, Factor F – level 1, Factor G – level 2, Factor H – level 1.
   For the Taguchi-regression method:
   Factor A – level 1, Factor B – level 1, Factor C – level 3, Factor D – level 1,
   Factor E – level 1, Factor F – level 3, Factor G – level 3, Factor H – level 1.
3. Comparing the increases in SNRs, using the Taguchi and the Taguchi-regression methods, we have the predicted gain of 4.4639 db and 3.9858 db, respectively, while gains of 2.1347 db and 3.2191 db through confirmation experiments, respectively. It shows that the Taguchi-regression method performs better than the Taguchi method in reproducibility.
4. The average error of 7.05% db in the Taguchi method and 5.50% in the Taguchi-regression method for the optimal setting, which makes process robustness, the Taguchi method has higher error than the Taguchi-regression method.
5. From the experimental results, both methods show a good prediction for the actual values; however, the Taguchi-regression method has a better fit.

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