

Abrasive wear response of TIG-melted TiC composite coating: *Taguchi approach*

M A Maleque¹, K A Bello^{1,2}, A A Adebisi¹ and A Dube³

¹ Department of Manufacturing and Materials Engineering, International Islamic University Malaysia, Darul Salam, 53100 Gombak, Selangor, Malaysia.

² Department of Metallurgical and Materials Engineering, Ahmadu Bello University Zaria, Nigeria

³ Ducom Instruments Ltd., Peenya Industrial Area Bangalore, KA-560 058, India.

E-mail: maleque@iium.edu.my

Abstract. In this study, Taguchi design of experiment approach has been applied to assess wear behaviour of TiC composite coatings deposited on AISI 4340 steel substrates by novel powder preplacement and TIG torch melting processes. To study the abrasive wear behaviour of these coatings against alumina ball at 600° C, a Taguchi's orthogonal array is used to acquire the wear test data for determining optimal parameters that lead to the minimization of wear rate. Composite coatings are developed based on Taguchi's L-16 orthogonal array experiment with three process parameters (welding current, welding speed, welding voltage and shielding gas flow rate) at four levels. In this technique, mean response and signal-to-noise ratio are used to evaluate the influence of the TIG process parameters on the wear rate performance of the composite coated surfaces. The results reveal that welding voltage is the most significant control parameter for minimizing wear rate while the current presents the least contribution to the wear rate reduction. The study also shows the best optimal condition has been arrived at A₃ (90 A), B₄ (2.5 mm/s), C₃ (30 V) and D₃ (20 L/min), which gives minimum wear rate in TiC embedded coatings. Finally, a confirmatory experiment has been conducted to verify the optimized result and shows that the error between the predicted values and the experimental observation at the optimal condition lies within the limit of 4.7 %. Thus, the validity of the optimum condition for the coatings is established.

1. Introduction

Arc welding is a major joining process which has found wide application in modern manufacturing processes. Among the various types of arc welding, tungsten inert gas (TIG) arc welding technology is being increasingly used as a suitable heat source for surface treatment of steel alloy components due to its attractive features such as flexible power requirement, limited heat inputs, highly autogenous [1-3]. Unlike conventional high-energy beam heat sources (such as laser and electron beams technology), the TIG fusion welding process is a low energy technique that guarantees quality weld surface with minimum defect and production cost. Due these inherent benefits, TIG arc surface melting and alloying is gaining popularity among the current trend in hardfacing (liquid phase surface) treatment of steels via incorporation of ceramic composite powder of desirable composition [4, 5].



TIG Ceramic-embedded coatings are being applied on engineering components employed in services where abrasive wear mostly occurs. A full understanding of the effects of TIG processing variables on the wear response is required to be established for the choice of optimal coating variable to reduce wear. A lower wear rate is one the main target of ceramic embedded coatings by TIG arc torch. Despite the technological simplicity of TIG glazing process, the number of processing parameters is too large and the factor-response correlation are not always known [6-8]. The optimization of the influencing parameters is therefore necessary from the point of view of obtaining a desirable functional deposited layer exhibiting lower wear rate. In most current coating development, the desired TIG processing parameters is determined by a trial-and-error procedure based on experience and handbook values. However, this is time-consuming, costly and does not insure that the selected input variables will result in optimal performance characteristics. In order to ease the optimization process, Taguchi design of experiment (DoE) approach which avoids the great number of experiment needed for a full factorial design could be very useful. Taguchi's method uses signal-to-noise ratio (S/N) to identify best parameter combinations and their levels, with the least variability, for optimization [7, 9]. In the present work, the Taguchi DoE approach was applied to study the TIG torch deposition of titanium carbide (TiC) hard coatings on near surface layer of AISI 4340 low alloy steel. The optimum combination of the control parameters (welding current, welding speed, welding voltage and argon gas flow rate) for obtaining minimum wear rate was investigated based S/N ratio.

2. Experimental procedure

2.1. Materials and specimen preparation

The ceramic material used for coating in this work was commercially available structural TiC, supplied by Sigma Aldrich USA (average size, 40 μ m; 99.9 wt. % purity). A commercial grade AISI 4340 low alloy steel sheet machined to nominal dimensions of 100 mm x 40 mm x 15 mm were acquired as the substrate material. The chemical compositions of the steel substrates are 0.42 percent C, 0.65 percent Si, 0.16 percent Mn, <0.05 percent S, <0.05 percent P, 0.75 percent Cr, 1.76 percent Ni and 0.24 percent Mo. The surfaces of the machined specimens were made flat by grinding to a surface roughness of about $R_a = 0.4 \mu\text{m}$ using SiC emery paper. This process was followed by degreasing in acetone and ethanol under ultrasonic waves for 20 minutes to remove any impurities such as grease, dust, and oxide layer from the substrate surface.

2.2. Composite coating deposition

The composite coatings based on TiC_p powder reinforcement were prepared by powder preplacement and TIG torch melting processes. In preplacing the powder, TiC powder with approximate content of 1.0 mg/mm² was mixed with a PVA (polyvinyl acetate) organic binder, distilled water and alcohol to form a ceramic paste. The paste was evenly preplaced on the cleaned substrate surface using a flat plastic spatula. After 30 minutes, the paste was dried in an electric oven at a lower temperature of 60 °C for 1 hour. The melting of the preplaced surfaces was achieved under the torch of a DCEN TIG arc welding machine (Model: Miller-Telwin TIG 165) to produce continuous coating tracks with overlapping ratio of 50 % for ball on disc tribo-wear tests. The surface coating was performed by traversing the preplaced specimen at 1 to 2 mm/s speed beneath the TIG arc with varying currents of 70-100 A and voltages of 20-35 V. A 3.2 mm diameter tungsten electrode was used to produce a stable arc length of about 2mm. Pure argon shielding gas was channelled at a flow rate of 10-25 l/min to prevent surface oxidation during irradiation. All the tracks were produced based on the plan of Taguchi L_{16} OA design. The essential features of TIG melting process are shown figure 1.

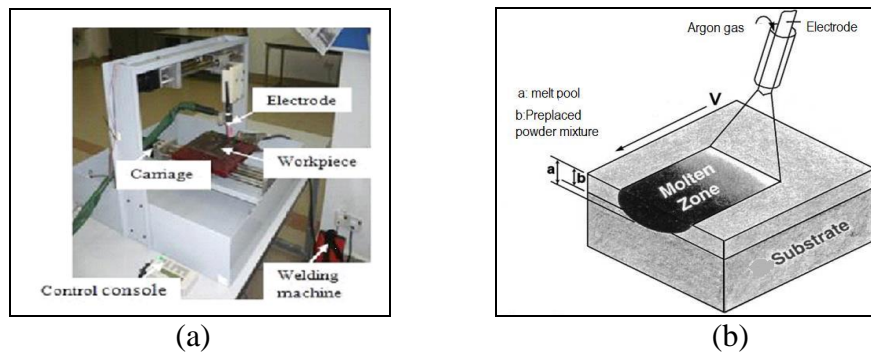


Figure 1. TIG welding process (a) photo of the machine (b) schematic of TIG glazing features.

2.3. Abrasive wear tests

The wear test was conducted using a DUCOM high-temperature tribometer (TR-20-PHM-CHM-600 model) with ball and disc contact geometry in rotating sliding motion. The rotating disc specimens for wear tests were machined to block with specified size of 26 mm x 10 mm x 10 mm. Alumina ball bearings with hardness of about 1800 Hv and maximum temperature of 1500-1800 °C were used as the static ball partner during the test. The test uses normal force of 10 N, rotating speed 0.2 m/s and a sliding distance of 500m. The sliding experiment was performed without lubrication at high temperature of 600 °C. After the test, the surface wear properties for each specimen were evaluated in terms of wear rate which was assessed by monitoring wear volume loss (V) using a standard formula [2]:

$$V = 2\pi R \{r^2 \sin^{-1}(d/2r) - d/4 \sqrt{4r^2 - d^2}\} \quad (1)$$

where R is the wear track radius (mm), d the wear track width (mm) measured with the aid of 3D non-contact profilometer, and r is the radius of alumina ball (mm). Thus, the wear rate (w) mm³/N was calculated from Eq. 2 [2]:

$$w = V / F_n l \quad (2)$$

where F_n represents the normal load applied to the samples and l is the sliding distance.

2.4. Taguchi design of experiment

The In Taguchi DoE, the most important stage is the selection of control parameters. Based on the extensive review of literature, parameters such as welding current, welding speed, welding voltage and argon gas flow rate were selected in this TIG hardfacing experiment and their effects were studied each specimen wear rate. The parameters and their corresponding levels are given in Table 1.

Table 1. Levels of the parameter used in the experiment.

Control Factor	Symbol	Units	Levels			
			1	2	3	4
Welding current	A	A	70	80	90	100
Welding Speed	B	mm/s	1.0	1.5	2.0	2.5
Welding voltage	C	V	20	25	30	35
Argon flow rate	D	L/min	10	15	20	25

A modified Taguchi array of L_{16} was used to plan the experiment. The details of the L_{16} (4^5) OA with five four-level factors is reported in the column 2, 3, 4 and 5 of Table 2. Each experimental run was repeated two times and the average value of the wear rate response was recorded. Furthermore, Taguchi S/N ratio analysis was used to evaluate the experimental data. Taguchi employs the S/N ratio to measure the quality characteristics deviating from the desired value. Based on the objective of this study, wear rate characteristic corresponds to the lower-the-better (LB) criterion and the S/N ratio (η_w) for wear rate is defined by [7, 9]:

$$\eta_w = -10\log(M.S.D) \quad (3)$$

where M.S.D is the mean square deviation for the output wear rate. Therefore, the M.S.D for the LB characteristic can be expressed as:

$$M.S.D = \frac{1}{n} \sum_{i=1}^n y_i^2 \quad (4)$$

where n is the number of experiments and y_i is the value of experimental result of the i th experiment. The results of S/N ratio for minimum wear rate are determined based on Eq. 3 and Eq. 4 using MINITAB 17 statistical software.

Table 2. Experimental design using L_{16} OA for wear rate of TiC composite coatings

Test run	Welding current, A: (A)	Welding peed, B: (mm/s)	Welding voltage C: (V)	Argon flow rate D: (L/min)	Wear rate, (mm^3/N)	S/N ratio (dB)
1	90.00	2.50	25.00	20.00	9.8072E-06	-19.8309
2	100.00	1.00	35.00	20.00	1.0825E-05	-20.6888
3	100.00	2.50	20.00	15.00	8.3717E-06	-18.4563
4	100.00	2.00	25.00	10.00	2.5134E-05	-28.0051
5	70.00	2.00	30.00	20.00	8.5910E-06	-18.6808
6	70.00	1.00	20.00	10.00	1.2182E-05	-21.7142
7	80.00	2.00	35.00	15.00	1.1809E-05	-21.4439
8	80.00	2.50	30.00	10.00	1.2262E-05	-21.7714
9	100.00	1.50	30.00	25.00	9.7859E-06	-19.8121
10	90.00	1.00	30.00	15.00	1.1206E-05	-20.9892
11	80.00	1.50	20.00	20.00	1.2645E-05	-22.0387
12	90.00	1.50	35.00	10.00	7.9527E-06	-18.0103
13	70.00	2.50	35.00	25.00	1.2795E-05	-22.1406
14	80.00	1.00	25.00	25.00	1.7089E-05	-24.6542
15	70.00	1.50	25.00	15.00	1.4426E-05	-23.1828
16	90.00	2.00	20.00	25.00	1.9787E-05	-25.9277

3. Experimental procedure

3.1. Abrasive Test Results and Taguchi Analysis.

In Table 2, the sixth and seventh column shows the experimental results for average wear rate and S/N ratio. The S/N ratio was computed and analysed using MINITAB 17 software. A greater S/N ratio value indicates better quality characteristics. As such, the optimal level of the control parameters is the level with the greatest S/N ratio. The level average responses from the S/N ratio data for wear rates of TiC embedded surface are summarized in Table 3. Accordingly, the difference between the maximum

and the minimum values (delta) is a decisive determinant of the influence of each parameter. The higher the delta value, the more influential the parameter appears. Therefore, the response table gives the significant trend with which each control factor affects the wear rate of TIG embedded coating when tested at 600 °C. It can be noticed from Table 3 that the welding voltage 'A' and the welding speed 'B' are the most important factor affecting the wear response. The argon gas flow rate 'C' has a less relevant effect, while the welding current shows the lowest effect among those factors.

Table 3. S/N response table for wear rate of TiC composite coatings

Factor		Level 1	Level 2	Level 3	Level 4	delta	Rank
Welding current	A	-21.43	-22.48	-21.19	-21.74	1.29	4
Welding Speed	B	-22.01	-20.76	-23.51	-20.55	2.96	2
Welding voltage	C	-22.03	-23.92	-20.31	-20.57	3.60	1
Argon flow rate, AFR	D	-22.38	-21.02	-20.31	-23.13	2.82	3

The main effects plots for wear rates of the three coating systems are presented as shown in figure 2. Analysis of the results from the response plots leads to the conclusion that factor combination of A₃ (90 A), B₄ (2.5 mm/s), C₃ (30 V) and D₃ (20 L/min) gives minimum wear rate for TiC embedded coatings.

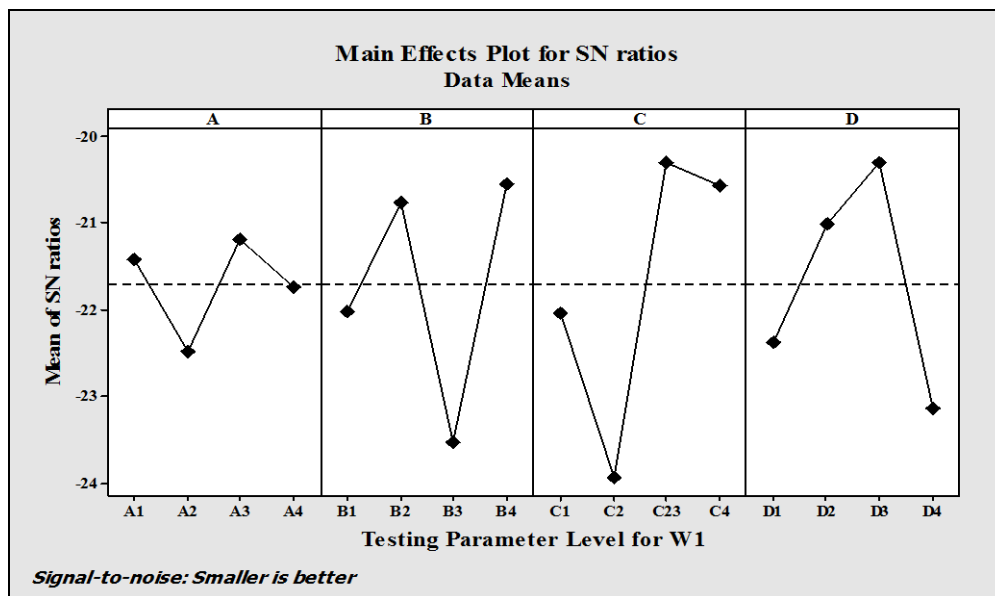


Figure 2. Influence of control factors on average S/N ratio for wear rate of TiC coatings.

3.2. Confirmation Experiment

The final stage of the Taguchi analysis is to conduct confirmation experiment by comparing the predicted value and the experimental results. In this process, a new set of experiment was performed using the optimal levels of the process parameters (A₃B₄C₃D₃) to predict the wear rate. The predicted S/N ratio for wear rate can be estimated with the aid of following predictive equation [9]:

$$\bar{\eta}_w = \bar{\eta}_m + \sum_{i=1}^k (\eta_i - \bar{\eta}_m) dB \quad (5)$$

where $\bar{\eta}_w$ is the predicted S/N ratio for wear rate response, $\bar{\eta}_m$ is the overall experimental average, η_i is the mean response for parameters at the optimal levels and k is the number of the control factors. Using predictive Eq. 5, the predicted S/N ratio ($\bar{\eta}_w$) for the wear rate was obtained from MINITAB 17 software and found to be $\bar{\eta}_w = -16.3069$. The experimental observations are then compared with the results obtained from the predictive equations. The percentage errors observed for the mathematical models are computed using the experimental value as reference. It is found that the percentage error observed for wear rate in TIG embedded TiC coating is 4.6 % for the S/N ratio value. Therefore, the resulting Taguchi model seems to be valuable for predicting wear rate to a reasonable accuracy.

4. Conclusion

This study shows that TIG torch can be used to produce TiC embedded composite coatings on LAS substrate. It is noticed that the wear rate of the ceramic-embedded layer is greatly affected by the processing parameter level of the TIG torch. Taguchi experimental design has been applied to analyze the influence of the control parameters on the wear rate of the coatings. Welding voltage and the welding speed are found to be the most influencing parameters for minimizing the wear rate. Argon gas flow rate and welding current are identified to have less relevant effect as far as the minimization of wear rates is concerned. The predictive based on Taguchi approach has been demonstrated to be consistent with the experimental observations. Therefore, the obtained results are satisfactory to a reasonable accuracy and can be used to investigate wear rate of any ceramic embedded composite coatings.

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