Optimization of tribological performance of SiC embedded composite coating via Taguchi analysis approach

M A Maleque, K A Bello, A A Adebisi and N Akma

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.

E-mail: maleque@iium.edu.my

Abstract. Tungsten inert gas (TIG) torch is one of the most recently used heat source for surface modification of engineering parts, giving similar results to the more expensive high power laser technique. In this study, ceramic-based embedded composite coating has been produced by precoated silicon carbide (SiC) powders on the AISI 4340 low alloy steel substrate using TIG welding torch process. A design of experiment based on Taguchi approach has been adopted to optimize the TIG cladding process parameters. The L9 orthogonal array and the signal-to-noise was used to study the effect of TIG welding parameters such as arc current, travelling speed, welding voltage and argon flow rate on tribological response behaviour (wear rate, surface roughness and wear track width). The objective of the study was to identify optimal design parameter that significantly minimizes each of the surface quality characteristics. The analysis of the experimental results revealed that the argon flow rate was found to be the most influential factor contributing to the minimum wear and surface roughness of the modified coating surface. On the other hand, the key factor in reducing wear scar is the welding voltage. Finally, a convenient and economical Taguchi approach used in this study was efficient to find out optimal factor settings for obtaining minimum wear rate, wear scar and surface roughness responses in TIG-coated surfaces.

1. Introduction

Metal components frequently lose functionality through severe environmental condition such as wear, corrosion, high temperature and high loading. In order to prevent such damages, advances in modification of critical engineering surfaces are frequently undertaken by researchers to extend the service life of engineering components [1, 2]. Over the years, this surface modification approach has been adopted by various industries, such as aerospace, petrochemical, automotive and general machinery [3]. The unique advantage of surface modification method is that the base material of the component can be selected for strength and price, while the surface properties can be altered independently for specific tribological conditions to which the critical sections of the part is subjected to in service [4-6].

Ceramic materials such as SiC particles are usually used in surface modification for improving tribological performances of steels because of their excellent physical and chemical properties. The incorporation of ceramic particles into molten metal surfaces to produce hard composite layers is popular because this method can tailor the surface to suite the requirements of specific applications.
High power laser and electron beam melting techniques have been used extensively for processing such composite layers, which are reported to increase wear and corrosion resistance significantly. However, these techniques are expensive and difficult and hence have a limited application. An alternative, more economical and novel method was developed using conventional TIG torch melting for surface modification work. This TIG surface melting process is simpler, cheaper to establish and flexible in operation, economical in time, energy and manufacturing procedure, compared to laser and electron beam processing [2, 8, 9].

Many authors have analyzed composite layer properties and characteristics under varying TIG welding conditions to [5, 6, 10]. It is evident from the studies that optimization of material surface properties largely depends on the understanding and control of the fusion process parameters that can influence both the mechanical and tribological performances of the reinforced composite layer. The TIG surface modification method is governed by many important parameters such as arc current, traveling speed, arc gap length, electrode size, argon gas flow rate and precoated powder content and composition [11]. Usually, the desired process parameters are determined based on experimental data and handbook values, which does not guarantee the chosen parameters will yield optimal performance characteristics. To obtain the best functional response of TIG processed coatings, a suitable design of experiment tool can be used to for precise identification of prominent factors for process optimizations. Recently, a robust empirical technique called Taguchi design has become widely known for parametric optimization in order to compensate for the shortcomings of conventional experimental methods. Unlike full factorial design, Taguchi requires minimal number of experiments to determine optimal process settings with least variability. Precisely, Taguchi’s is a simple and efficient approach to optimize designs for quality and performance at a minimum cost and time [8, 10-11].

In the present study, Taguchi experimental design based on L9 orthogonal array was used in investigating the effect of essential TIG control parameters on wear rate, wear track widths and surface roughness of the TIG-processed SiC composite coatings. Moreover, the optimal parameters for processing SiC-embedded coating on AISI 4340 steels were established.

2. Experimental details

2.1. Materials

AISI 4340 low alloy steel with the dimension of 100 mm × 45 mm × 14 mm was used as the substrate material in this work. The surface of the base material were ground using silicon emery paper and thoroughly cleaned in acetone to remove all the contaminants in form of oxide layers and grease. The chemical composition of the steel substrate can be found elsewhere [4]. Silicon carbide powder (99.5% purity, 40-50 µm) supplied by Sigma Aldrich was used for surface alloying. The SiC particulates weighed at the proportion of 0.5 mg/mm² was mixed with organic binder (PVA) and preplaced onto the surface of the dry substrate samples. Organic binder was primarily used to prevent the powders from blowing away under the flow of shielding gas during TIG glazing operation. The pre-coated substrates were then dried in an oven to remove moisture before surface irradiation under TIG arc torch. Further experimental detail on this process can be found elsewhere [2, 5].

2.2. Planning experiment

The design of experiments involves the use of statistical tools to analyze the effects of controllable factors on the response performances. Taguchi design approach was used for planning of experimental runs in this study. Taguchi method is well known to be simple and efficient for optimizing and improving performance by using standard orthogonal arrays (OA) with minimal number of experiments. In this study, the effect of TIG process variables such as welding current, travel speed, arc voltage and argon gas flow rate are considered to be studied using standard Taguchi L9 (3^4) design. The L9 OA chosen in this study is a modified Taguchi array that can accommodate up to 4 factors at three levels. The individual effects of all the factors are studied on the response variable on
order to obtain optimal TIG welding parameters that would yield best tribological behavior. The tribological response variable in this case are wear rate, wear tracks width and surface roughness. Nine experiments are required by Taguchi L9 array to optimize the TIG welding parameters. The factor levels and their corresponding response are assigned to the columns of the modified array as shown in Table 1.

Table 1: The design matrix for experimental runs

| Experimental Runs | Current (A) | Speed (mm/s) | Voltage (V) | Argon flow rate (L/min) | Wear rate µg/cm | Wear tracks width (µm) | Surface roughness (µm) |
|-------------------|-------------|--------------|-------------|-------------------------|-----------------|------------------------|------------------------|
| 1                 | 70          | 1.0          | 20          | 15                      |
| 2                 | 70          | 1.5          | 25          | 20                      |
| 3                 | 70          | 2.0          | 30          | 25                      |
| 4                 | 80          | 1.0          | 25          | 25                      |
| 5                 | 80          | 1.5          | 30          | 15                      |
| 6                 | 80          | 2.0          | 20          | 20                      |
| 7                 | 90          | 1.0          | 30          | 20                      |
| 8                 | 90          | 1.5          | 20          | 25                      |
| 9                 | 90          | 2.0          | 25          | 15                      |

2.3. Developing surface coating
Surface melting was performed using TIG process. A thoriated tungsten electrode (3.6Ø mm) was used to generate a stable arc for the glazing action at a fixed height of 2 mm from the sample. The energy density of the TIG torch was controlled by the supply of current and voltage to produce series of multiple overlap tracks. Details of the processing conditions used in this work are presented in columns 2, 3, 4 and 5 of Table 1. During the melting process, a streamed of pure argon gas was supplied to avoid excessive oxidation of the molten pool.

2.4. Tribological tests
The wear behavior of the SiC embedded steel was assessed using CSM ball-on-disk tribometer for 30 minutes duration at 30.6 N load, constant speed (100 rpm) under dry non lubricated condition and at ambient temperature (30°C). The embedded steel samples have the dimension of 10 mm × 15 mm × 11 mm were mechanically fixed chamber and alumina ball was used as a counterpart material. The track radius was fixed for all trial of experiments at 3 mm. The wear rate was calculated based on the relationship in Equation 1:

\[
\text{Wear rate, } W_r = \frac{\Delta w}{2\pi r n t}
\]

where \( W_r \) is the wear rate in terms of volume loss, \( \Delta w \) is weight loss, \( n \) is revolution per minute, \( r \) is the radius of ball distance from the centre of the steel disc and \( t \) is the sliding time.

3. Results and discussion

3.1. Wear rate analysis
The results of experiments obtained for wear rate of SiC embedded low alloy steel under selected conditions of TIG melting processes are presented in the second column of Table 3. Based on Taguchi approach, the results of the quality characteristic are transformed into signal-to-noise (S/N) ratio for
the optimum parameter analysis. The S/N ratio for minimum wear rate can be determined based on the smaller-the-better (STB) criterion, which is calculated as logarithmic transformation of loss function as shown below:

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

Where \( n \) is the number of experiment, \( Y \) is the experimental data and \( S/N \) is the signal-to-noise ratios for wear rates. However, the concept (“smaller-the-better”) was equally applicable to surface roughness and wear track widths performance index assessment purposes. The signal-to-noise ratio is measured in decibel scale (dB) and the results calculated using Eq. (2) is given in Table 2. The analysis of S/N ratio is done by computing the mean of the S/N ratio for each level of TIG welding parameters. The separation of each process parameter by S/N ratio is done based on the experimental design array is orthogonal. The S/N ratio single-response Table for wear rate is presented in Table 3.

### Table 2: Results of wear rate with S/N ratio

| Expt. no | Wear rate (\( \mu g/cm \)) | S/N ratio (dB) |
|----------|----------------------------|----------------|
| 1        | 1.39703                    | -2.90409       |
| 2        | 1.46776                    | -3.33310       |
| 3        | 1.27320                    | -2.09793       |
| 4        | 1.75070                    | -4.86425       |
| 5        | 1.30861                    | -2.33619       |
| 6        | 2.19280                    | -6.81999       |
| 7        | 1.89217                    | -5.53923       |
| 8        | 1.27324                    | -2.09820       |
| 9        | 1.39703                    | -2.90409       |

### Table 3: S/N ratio response table for wear rate

| Levels | Current (A) | Speed (mm/s) | Voltage (V) | Argon flow rate (L/min) |
|--------|-------------|--------------|-------------|-------------------------|
| 1      | -2.778      | -4.436       | -3.941      | -2.715                  |
| 2      | -4.673      | -2.589       | -3.700      | -5.231                  |
| 3      | -3.514      | -3.941       | -3.324      | -3.020                  |
| Delta  | 1.895       | 1.849        | 0.616       | 2.516                   |
| Rank   | 2           | 3            | 4           | 1                       |

It can be observed from Table 3 that the effect of argon flow rate and current are ranked higher and are considered to be very significant whereas welding voltage and speed are found to have slightly effects on the performance characteristic. However, the aim of the analysis is to identify the levels of the combining factors which present minimum wear rate. Figure 1 shows the influence of process
variables on the wear rate. As far as the minimization of wear rate is concerned, the results of S/N response analysis indicate that the optimal combination of parameters occur at factor levels corresponds to the current of 70 A, speed of 1.5 mm/s, voltage of 30 V and argon flow rate of 15 L/min.

![Main Effects Plot for SN ratios](image)

**Figure 1.** Main effects plot for wear rate of SiC embedded LAS under TIG torch melting.

### 3.2. Wear tracks width Analysis

The second response which is wear tracks width for each TIG torch process parameters at different levels were calculated. The normal method of calculating the desirable factors levels is to look at simple averages of the results. However, the variability of results within a trial condition cannot be judged by this method. Thus, signal-to-noise ratio analysis is done considering wear tracks width as the performance index. The analysis is carried out using the smaller-the-better (STB) criterion and is expressed as Equation 2. Table 4 shows the experimental results for wear tracks width tests and the corresponding S/N ratio for each experiment. Since the experimental design is orthogonal, it is possible to separate out the effect of each control factor at different levels. All the calculations are performed using Minitab software. The S/N response table shown in Table 5 includes ranks based on Delta value (the highest average of each factor minus the lowest average of the same); rank 1 is assigned to the parameter with highest Delta value, rank 2 to second highest Delta value and so on. In this case voltage has the highest Delta value thus rank 1 is assigned to voltage (V). The corresponding main effects plot for S/N ratio is shown in figure 2. The significance of each parameter can be judged by the inclination of plot. The parameter with highest inclination line has greater significance than the rest on the wear behaviour of the material. From the main effects plot, it is seen that the parameter voltage V is the most significant parameter while other parameters, argon flow rate (L/min) and speed (mm/s) are also significant parameters in controlling the wear behavior of the coated steel samples. The optimal process parameter combination is the one that yields minimum S/N ratio and thus the same for minimum wear tracks width is found to occur at a current of 70 A, speed of 1.0 mm/s, voltage of 25 V and argon flow rate of 15 L/min.
Table 4: Results of wear tracks width with S/N ratio

| Expt. no | Wear tracks width (µm) | S/N ratio (dB) |
|----------|------------------------|----------------|
| 1        | 212.156                | -46.5331       |
| 2        | 250.251                | -47.9675       |
| 3        | 560.991                | -54.9791       |
| 4        | 293.118                | -49.3408       |
| 5        | 356.213                | -51.0342       |
| 6        | 346.486                | -50.7937       |
| 7        | 480.862                | -53.6404       |
| 8        | 352.109                | -50.9335       |
| 9        | 264.624                | -48.4526       |

From the main effect plots in Figure 2, the effects of individual process parameters on the wear tracks width of the composite coated steel can be clearly seen. Thus, from figure 2, it is observed that wear tracks width decreases with highest of voltage, followed by argon flow rate and speed. However, current has almost no effect on wear tracks width.

Table 5: S/N ratio response table for wear tracks width

| Levels | Current (A) | Speed (mm/s) | Voltage (V) | Argon flow rate (L/min) |
|--------|-------------|--------------|-------------|-------------------------|
| 1      | -49.83      | -49.84       | -49.42      | -48.67                  |
| 2      | -50.39      | -49.98       | -48.59      | -50.80                  |
| 3      | -51.01      | -51.41       | -53.22      | -51.75                  |
| Delta  | 1.18        | 1.57         | 4.63        | 3.08                    |
| Rank   | 4           | 3            | 1           | 2                       |

Figure 2. Main effects plot for wear tracks width of SiC embedded LAS under TIG torch melting.
3.3. Surface roughness analysis

Table 6 shows the effect of various factors i.e. current, speed, voltage and argon flow rate on the surface roughness of SiC embedded alloy steel after wear test. The response analysis of S/N ratio is done by computing the mean of the S/N ratio for each factor level. The separation of each process parameter by the S/N ratio was possible since the experimental design array was orthogonal. The S/N ratio single-response table for surface roughness is presented in Table 7. Since the surface roughness is a ‘smaller the better’ type of quality characteristic and because the objective is to minimize the surface roughness, therefore, the S/N ratio for ‘smaller the better’ type of response was used as given in Equation (2) for wear rate.

| Expt. no | Surface roughness (µm) | S/N ratio (dB) |
|----------|------------------------|----------------|
| 1        | 7.2096                 | -17.1582       |
| 2        | 5.8929                 | -15.4066       |
| 3        | 6.6398                 | -16.4431       |
| 4        | 9.1722                 | -19.2495       |
| 5        | 13.7000                | -22.7344       |
| 6        | 3.2907                 | -10.3458       |
| 7        | 4.7235                 | -13.4853       |
| 8        | 9.3172                 | -19.3857       |
| 9        | 9.0207                 | -19.1048       |

From the results of Taguchi analysis shown in Table 7, it is clear that argon flow rate (AFR) is the most significant factor on the surface roughness, followed by travel speed, welding voltage and current. The delta contribution of argon flow rate to the surface roughness is 6.59. Figure 3 shows that the higher S/N ratio corresponds to higher performance characteristics. Hence, the optimal combination of parameters for minimum surface roughness can be seen in Figure 3 as the current of 70 A, speed of 2.0 mm/s, voltage of 20 V and argon flow rate of 20 L/min.

| Levels  | Current (A) | Speed (mm/s) | Voltage (V) | Argon flow rate (L/min) |
|---------|-------------|--------------|-------------|-------------------------|
| 1       | -16.34      | -16.63       | -15.63      | -19.67                  |
| 2       | -17.44      | -19.18       | -17.92      | -13.08                  |
| 3       | -17.33      | -15.30       | -17.55      | -18.36                  |
| Delta   | 1.11        | 3.88         | 2.29        | 6.59                    |
| Rank    | 4           | 2            | 3           | 1                       |
4. Conclusion

Based on the analysis of the experimental result using Taguchi method, the following conclusions can be draw from the present studies on dry sliding wear test for SiC composite coatings developed by TIG torch surface melting technique:

1) The optimal combination of process parameters for minimum wear rate is found to be a current of 70 A, speed of 1.5 mm/s, voltage of 30 V and argon flow rate of 15 L/min. Meanwhile for wear tracks width, the optimal processing parameters occurs at a current of 70 A, speed of 1.0 mm/s, voltage of 25 V and argon flow rate of 15 L/min and the analysis of surface roughness resulted in optimal parameter levels of 70 A current, speed of 2.0 mm/s, voltage of 20 V and argon flow rate of 20 L/min.

2) Argon gas flow rate has the highest influence on the general tribological performance of SiC embedded coatings.

3) The application of Taguchi approach was successful for optimizing tribological behavior of SiC embedded coating on LAS in this study and can also be applied in optimizing other coating performance characteristics.

Acknowledgement

The authors acknowledge the financial assistance from Research Management Center of International Islamic University Malaysia under the grant no RMGS-12-007-0020.

References

[1] Bell T, Morton P H, Bloyce A 1994 Mater Sci Eng. 184 73-86.
[2] Adeleke S A and Maleque M A 2014 Adv. Mater. Res. 1024 207-210.
[3] Kirchgabner K, Badisch E and Franek F 2008 Wear 265 772-777.
[4] Maleque M A, Bello K A, Idriss A N M and Mirdha S 2013 Appl. Mech. Mater. 378 259-264.
[5] Mirdha S, Idriss A N M, Maleque M A, Suryanto S and Souad A 2012 Intl. J. of Mech Mater Eng. 7 48-53.
[6] Ulutan M, Yildirim M, Buytoz S and Celik O N 2010 Tribol T 54 67–69.
[7] Buytoz S 2006 Surf Coat Technol. 200 3734-42.
[8] Bello K A, Maleque M A, Zuraida A and Mirdha S 2015 Adv Mater Res. 115 238-242.
[9] Maleque M A, Ghazal B A, Ali M Y and Ahmed A S 2015 Mater Sci Forum, 819 76-80.
[10] Pasupathy J and Ravisankar V 2013 Int J Sci Eng Res. 4 25-28.
[11] Peng D X 2012 Ind. Lubr. Tribol. 64 303-311.