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Taguchi Optimization of Wear Properties of Duplex Stainless Steel Reinforced Surface with Silicon Carbide Using TIG Torch Melting

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ABSTRACT

This work presents experimental and numerical results of deposition of SiC coating using TIG torch method. The Taguchi approach was used to optimize the TIG torch melting process of duplex stainless steel for increasing the wear properties. The process variables used are current, voltage, transverse speed and gas flow rate. The parameter combinations were carefully chosen with the purpose of producing a hard surface layer with the enhancement of wear properties. Three levels of parameters were used in the experimental design in accordance with L9 orthogonal array. The signal-to-noise (SN) ratio was employed to analyze the experimental data. The results show that the current provides the most influencing parameter while the transverse speed provides the least contribution on the improvement of wear properties. The optimize parameter on the hardness and wear rate is 80 A of current, 20 V of voltage, 1.0 mm/sec of transverse speed and 25 L/min of argon flow rate. The main worn surface mechanism for SiC-DSS reinforced surface exhibited mild striation for the best sample of hardness and wear resistance.

Keywords: *Taguchi, Silicon carbide, Duplex stainless steel, Optimization, Wear*

1. INTRODUCTION

Due to the high power density and precise control of the laser beam, the manufacturing of a clad layer via a laser cladding approach has received significant consideration in order to improve the surface feature of a bulk component. Previous researchers successfully used the approach using the powder blown, wire feeding, and preplaced powder techniques [1,2,3]. However, the laser cladding was discovered to be uneconomical for wide area overlay coating by overlapping the tracks due to the expensive and lower absorptivity of the laser beam by metallic power. On the other hand, the TIG cladding process is a cost-effective technology that permits the production of a single line clad layer as a large-area overlay coating that systematically overlaps the tracks [4,5,6]. On numerous structural materials including steel, Ti alloy, and Al alloy, some researchers had used the TIG process to construct a single line clad layer of hard and corrosion-resistant materials [7,8,9].

Due to this, the wear applications require wide area of the surface modification. High speed machine parts go through rigorous and unpleasant working situations. The materials used in manufacturing processes that are in constant contact with one another experience significant energy loss and have a shorter component life. Numerous tribologists have become interested in surface modification using the cladding technique to enhance the surface property for applications requiring wear resistance. Stainless steel is one of the most widely used materials in the various applications such as oil and gas, aircraft and automotive applications. However, this material has a disadvantage due to its low tribological resistance properties. Due to this, surface modification is required to improve the surface properties of this material to expand its use to various applications.

Duplex stainless steel (DSS) is a common substance in the chemical and structural sectors. The modification of the surface characteristic may be the remedy to the aforementioned issue. Therefore, this work is carried out to examine the enhancement of the wear properties by depositing the ceramic particle into the DSS by TIG torch melting. This melting technique has greater influence on weld zone, mechanical properties and microstructure. To optimize the TIG welding parameters, design of experiment is designed using Taguchi orthogonal array technique.

The Taguchi technique is an effective tool for creating high-quality systems and is frequently used to raise quality without raising costs or requiring too much experimentation. It offers a simple, effective, and comprehensive method to improve designs' performance, quality, and price. When process parameters are qualitative and discrete, this technique is useful. By adjusting process parameters, the Taguchi technique parameter design can improve quality attributes and minimize the sensitivity of system performance to sources of variation [10]. In practice, the Taguchi method was developed to improve a specific quality attribute.

Peng [11] investigated the effects of TIG welding parameters on wear performance of clad layer with TiC ceramic of carbon steel. It is found that the welding current and welding speed gave the significant effect on cladded layer hardness and wear resistance of carbon steel. The high welding current and low welding speed caused the reduction of the hardness of the clad layer. The wear scar area and depth were independent of both electrode gap size and argon gas flow rate. Kumar et al. [12] conducted the process optimization using Taguchi method to understand the effect of process parameters of pulsed current TIG torch welding on aluminum alloy weldments. Five important process parameters of pulsed current TIG welding were used with gas mixtures to optimize the four quality characteristics of mechanical properties such as tensile strength, microhardness and elongation.

Furthermore, as per the author's knowledge, no literature is available regarding the formation of SiC reinforcement on DSS. In the present work, the Taguchi approach was performed on preplaced SiC powder to obtain the optimize parameter on wear enhancement. The wear characteristic of the clad layed for different current, voltage, transverse speed and gas flow rate was also analyzed through wear test performed in a ball-on-disc tribometer.

2. MATERIALS AND METHODS

2.1. Materials and SiC particles deposition on DSS surface

The SiC was originally deposited on a DSS steel plate (50 mm x 33 mm x 10 mm) for the SiC-DSS coating. The DSS materials were from Japan's Outokumpu, Mitsui, Sumitomo, Tokyo. Due to the cost and weight savings (pressure vessels) of AISI Duplex-2205 over AISI 316L, this grade was chosen. Additionally, around 85% of the existing duplex manufacturing is made up of AISI Duplex-2205 grades. The DSS plate's surface underwent a milling procedure to remove any undesired material such as swarf and manufacturing remnants to produce a smooth surface for the sample. The sample was then carefully cleaned in acetone and running water after being ground using silicon emery paper.

The surface properties of DSS were improved in this study by using silicon carbide with particle sizes of 20 μm (provided by Innovative Pultrusion Sdn. Bhd.). Prior to TIG arc cladding, the ceramic particle was deposited on the surface material for surface modification. By combining 2 drops of polyvinyl acetate (PVA), one drop of alcohol and distilled water into the SiC powder, the SiC paste was formed. To remove the moisture of the SiC paste and ensure that the ceramic particles adhered consistently to the substrate surface during the TIG arc melting process, the paste form was then deposited on the surface material and heated in the furnace for 1 hour while maintaining a temperature of 80 °C.

2.2 Design of Experiment

The experimental results are assessed by Taguchi S/N ratio analysis. To determine whether quality aspects deviate from the target value, Taguchi applies the S/N ratio. Higher values for surface hardness properties and lower values for wear rate and CoF. The process parameter optimizations for TIG melted DSS is based on the larger-the-better (LTB) criterion for hardness characteristic and the smaller-the-better (STB) criterion for wear rate and CoF. Using the following equations, the performance characteristic for the optimization criterion was assessed [13];

$$S/N\ (LTB) = -10*\log\left(\Sigma\ (1/Y^2)/\eta\right) \quad (1)$$

$$S/N\ (STB) = -10*\log\left(\Sigma\ (Y^2/\eta)\right) \quad (2)$$

Where,
η = number of experimental run in a trial/row,
Y= performance value obtained for each respective trial/row.

Current, voltage, transverse speed and argon flow rate are the input factors for the surface coating process for TIG torch melting. The design matrix is carried out in accordance with the experimental design summarized in Table 1 where each column is a process parameter, and each row denotes a test condition representing a combination of parameter levels. The response is presented in terms of hardness, wear rate and coefficient friction (CoF). There were three levels specified for each independent variable. The appropriate Taguchi design to apply is the L9 orthogonal array because there are 4 factors, each with 3 levels as shown in Table 2. The hardness performance, wear rate and coefficient of friction (CoF) of the TIG-processed SiC reinforced composite coated DSS under dry conditions are designed and analyzed using this method.

Table 1 Levels of the parameter used in the experiment

Control Factor	**Levels**		
	1	**2**	**3**
Current (A)	80	90	100
Voltage (V)	20	30	40
Transverse speed (mm/s)	1	1.5	2.0
Argon flow rate (L/min)	15	20	25

Table 2 Experimental Design Matrix for SiC-DSS reinforced surface using TIG torch melting process

Experiment No.	Factor			
	1	2	3	4
	Current (A)	Voltage (V)	Transverse Speed (mm/s)	Argon flow rate (L/min)
1	80	20	1	15
2	80	30	1.5	20
3	80	40	2	25
4	90	20	1.5	25
5	90	30	2	15
6	90	40	1	20
7	100	20	2	20
8	100	30	1	25
9	100	40	1.5	15

2.3 SiC Deposition on Duplex Stainless Steel using TIG torch melting process

A tungsten electrode containing 2% thorium is utilized as a welding electrode. To make an electrode which can enhance melting temperature, arc stability, and emissivity during the process, the thorium components are blended with the tungsten electrode. It has a diameter of 3.2 mm, and a length of 150 mm. Pure argon was utilized as a shielding gas during the melting process to prevent the molten pool from the oxidation that can contributes to the defects on the weld track. The complete processed of the SiC-DSS sample was cleaned using running water to remove the excessive ceramic particles on the surface. The cross-section was then sliced using a wire cut electrical discharge machine (EDM). The samples were then subjected to the metallography grinding and polishing process for thorough studies.

2.4 Vickers Micro Hardness

A pyramid diamond indenter with a 500 gf load and a 10-second indentation period was used in a Vickers micro-indentation hardness tester (model: Wilson Wolpert) to measure the hardness values. By measuring the micro-hardness value at the center region of a single track from the top surface towards the substrate material, the hardness pattern of the clad layer cross-section was determined. Each sample underwent five indentations, and the average measurement was reported as a result.

2.5 High Frequency Reciprocating Rig - Wear Test

The samples were evaluated using a linear reciprocating wear test utilizing the ball-on-disc method (model: Ducom TR-281-M8) in accordance with ASTM D6079 to determine the wear rate and coefficient of friction. The samples were cut into rectangular sections of 15 mm x 15 mm with thickness of 6 mm using an EDM wire cut machine. To achieve smooth contact between the SiC-DSS coated layer and counterpart material of the alumina ceramic ball, the sharp edges and undesirable impurities that were present on the surface clad layer were refined with 400 and 800-grade sandpaper. The wear test is carried out using linear motion at frequency of 5 Hz and load of 30 N. Figure 1 illustrates the test circumstances and a schematic of the linear motion of an alumina ceramic ball on the SiC-DSS clad layer. Weight balance was used to calculate the wear rate value in terms of weight loss of the SiC-DSS clad layer. The coefficient of friction was immediately recorded by the Winducom Software from the machine. For every sample, each measurement is made three times. Equation 3 shows how to compute the wear rate and represent it as mm^3/Nm. Additionally, a scanning electron microscope (SEM) analysis is performed on the surface morphology pattern after the linear motion reciprocating test.

$$\text{Wear rate} = \frac{\text{Weight loss(g) / density (g/mm}^3\text{)}}{\text{(Normal load(N) x reciprocating distance (m)}} \quad (3)$$

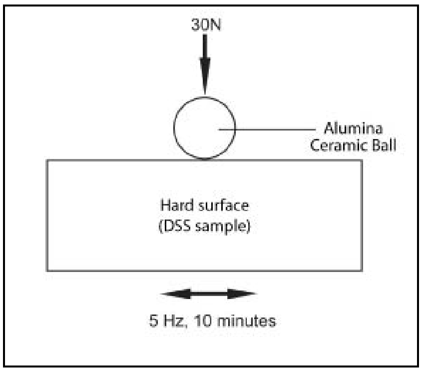


Figure 1. Schematic representation of the linear motion of alumina ceramic ball on the SiC-DSS reinforced surface.

3. RESULTS AND DISCUSSION

3.1. Vickers Microhardness

The hardness results for SiC-DSS reinforced surface was presented in Table 3. The larger-the-better characteristic with signal to noise ratio analysis was carried out, which leads to the maximization of surface hardness. The influence of the selected TIG process parameters (welding current, voltage, transverse speed and argon gas flow rate) on the surface hardness responses were analyzed using mean S/N response analysis as per Taguchi method.

Since the experimental design is orthogonal, it is possible to separate out the effect of each control factor at different levels. The S/N response table shown in the Table 4 includes ranks based on Delta value (difference between the highest and lowest average response values for each factor); rank 1 is assigned to the parameter with highest Delta value, rank 2 to second highest Delta value and so on. Table 4 shows the mean S/N ratio response for hardness of SiC-DSS reinforced surface. It is indicated that the current (A) has the greatest impact on hardness performance followed by argon flow rate (D) and voltage (B). Transverse speed (C) is non-significant parameter and least effect on the hardness performance of SiC-DSS reinforced surface. The presence of SiC ceramic particles contributed to the improvement of TIG torch melted layer DSS which achieved the hardness value of 514.5 to 1000 HV as compared to substrate DSS of 250 HV. The mean S/N ratio response suggested that the argon gas flow rate exhibited second intense effect on the dissolution of SiC ceramic particles together with substrate dilution. However, it is recommended to keep the gas flow rate in appropriate level to ensure the stability of the arc heat input. Applying higher gas flow rate could make the arc unstable [14].

Table 3 Vickers hardness value of SiC-DSS reinforced surface and S/N ratio

Experiment No.	Vickers hardness (HV)	S/N ratio (dB)
1	922.7	59.3012
2	833.6	58.4192
3	**1000 (best)**	**60.0000**
4	922.7	59.3012
5	659.3	56.3817
6	898	59.0655
7	701.9	56.9255
8	720	54.227
9	**514.5 (worst)**	**54.227**

Table 4 Mean responses for hardness S/N ratio of SiC-DSS reinforced surface

Process parameter	Symbol	Mean S/N ratio (dB)			Max-Min (delta)	Rank
		Level 1	Level 2	Level 3		
Welding current	A	59.24	58.25	56.10	3.14	1
Welding voltage	B	58.51	57.32	57.76	1.19	3
Transverse Speed	C	58.50	57.32	57.77	1.19	4
Argon flow rate	D	56.64	58.14	58.82	2.18	2

Figure 2 shows the main effects for S/N ratios for hardness of SiC-DSS reinforced surface. This graphical representation allows the evaluation of the effects of process parameters on the surface hardness. Accordingly, the level of a parameter with the highest S/N ratio gives the optimal level. Based on the maximization principles, it was found that the means and S/N ratio values that the optimal level setting for surface hardness is 80 A (A1), 20 V (B1), 1.0 mm/sec (C1) and 25 L/min (D3). Thus, this result leads to the conclusion that the best factor combination values for maximum surface hardness development of the SiC-DSS reinforced surface with 20 μm silicon carbide is A1B1C1D3.

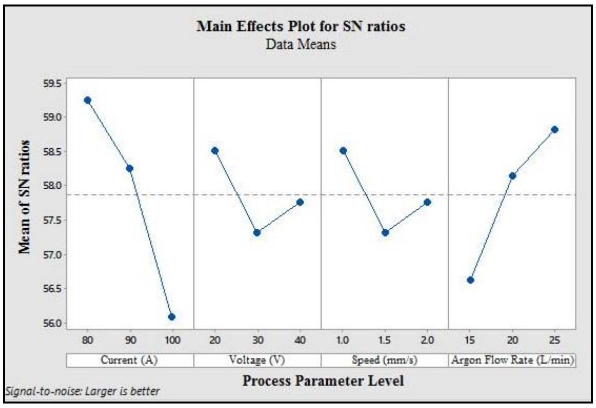


Figure 2. Influence of process parameters on mean S/N ratio for hardness of SiC-DSS reinforced surface.

3.2 Wear Rate Analysis

Wear rate characteristics of SiC-DSS reinforced surface were analyzed using single response technique. The tribological test using ball-on-disc method at room temperature was done to determine the wear rate for SiC-DSS reinforced surface as presented in Table 5 with their S/N ratio. As the wear rate to be minimized, the criterion of S/N ratio data was obtained using the smaller-the-better criterion.

Table 5 Wear rate value of SiC-DSS reinforced surface and S/N ratio

Experiment No.	Wear rate x10^{-4} (mm^3/Nm)	S/N ratio (dB)
1	3.2	-10.1030
2	3.5	-10.8814
3	**3.2 (Best)**	-10.1030
4	3.2	-10.1030
5	4.4	-12.8691
6	3.5	-10.8814
7	4.3	-12.6694
8	4.3	-12.6694
9	**5.5 (Worst)**	-14.8073

Table 6 shows the response results for wear rate of SiC-DSS reinforced surface. The most powerful influence of parameters which influences the wear rate is welding current followed by gas flow rate and voltage. Transverse speed (C) emerged as the least significant factor affecting the wear rate of SiC-DSS reinforced surface. It is worthy to mention that welding current is correlated well with heat input. The appropriate heat input contributed significantly to the melting of substrate and SiC ceramic particles with more dissolution in TIG melted layer. The melt was more fluid and created greater precipitation of SiC particles in TIG melted layer. This result is quite closely in agreement with the previous result presented by Mridha et al. [15] whereby TiC was preplaced on low alloy steel.

Table 6 Mean Responses for Wear Rate of TIG Torch Melted DSS Using 20 µm SiC Particle Size (WR1)

Process parameter	Symbol	Mean S/N ratio (dB)			Max-Min (delta)	Rank
		Level 1	Level 2	Level 3		
Welding current	A	-10.36	-11.28	-13.38	3.02	1
Welding voltage	B	-10.96	-12.14	-11.93	1.18	3
Transverse Speed	C	-11.22	-11.93	-11.88	0.71	4
Argon flow rate	D	-12.59	-11.48	-10.96	1.63	2

The main effects plots in for S/N ratio in Figure 3 shows the optimum combination of SiC-DSS reinforced surface for obtaining minimum wear rates. It can be seen that the parameter optimization for wear rate is 80 A, 20 V, 1 mm/s and 25 L/min under symbol of A1, B1, C1 and D3 (as stated in Table 1).

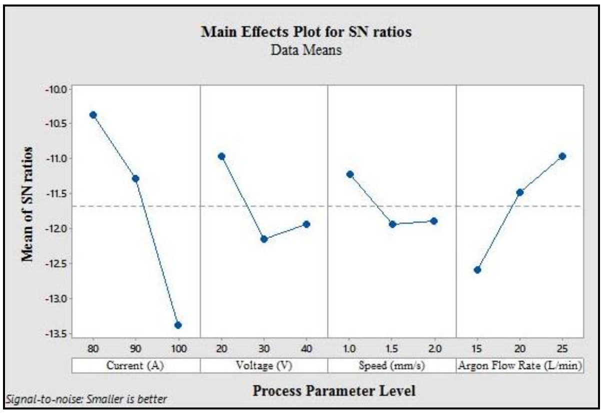


Figure 3. Influence of process parameters on mean S/N Ratio for wear rate SiC-DSS reinforced surface.

3.3 Coefficient of Friction (CoF) Analysis

The CoF results with their S/N ratio of SiC-DSS reinforced surface is shown in Table 7. The evaluation of the CoF is similar with wear rate which the value is to be minimized. Therefore, the criterion of S/N ratio data was obtained using the smaller-the-better criterion. The mean responses for CoF of SiC-DSS reinforced surface is presented in Table 8. It can be seen that the welding current has the highest Delta value thus rank 1 is assigned to current (A). This is followed by second, third and fourth highest of delta value which are welding voltage, argon flow rate and transverse speed, respectively.

From the main effects plot In Figure 4, it can be seen that the parameter of welding current (A) is the most significant parameter while other parameters, argon flow rate (L/min) and transverse speed (mm/s) are also significant parameters in controlling the CoF value of the SiC-DSS reinforced surface. The optimal process parameter combination is the one that yields minimum S/N ratio and thus the same for minimum CoF is found to occur at a current of 80 A, welding voltage of 20 V, transverse speed of 1.0 mm/s and argon flow rate of 20 L/min.

Table 7 CoF value of SiC-DSS reinforced surface and S/N ratio

Experiment No.	CoF	S/N ratio (dB)
1	0.45	-13.0643
2	0.48	-13.6248
3	**0.44 (best)**	-12.8691
4	0.46	-13.2552
5	0.63	-15.9868
6	0.45	-13.0643
7	0.60	-15.5630
8	0.68	-16.6502
9	**0.68 (worst)**	-16.6502

Table 8 Mean responses for CoF of SiC-DSS reinforced surface

Process parameter	Symbol	Mean S/N ratio (dB)			Max-Min (delta)	Rank
		Level 1	Level 2	Level 3		
Welding current	A	-13.19	-14.10	-16.29	3.10	1
Welding voltage	B	-13.96	-15.42	-14.19	1.46	2
Transverse speed	C	-14.26	-14.51	-14.81	0.55	4
Argon flow rate	D	-15.23	-14.08	-14.26	1.15	3

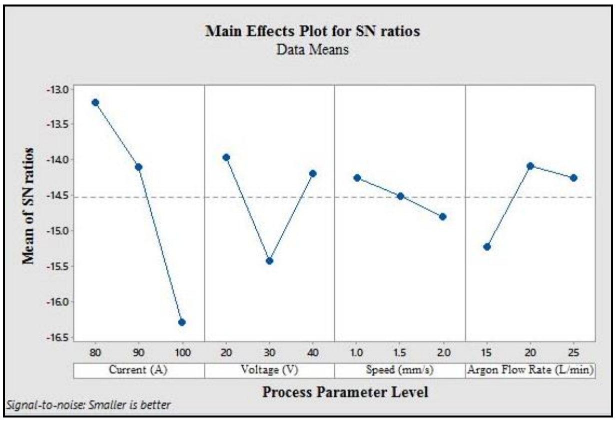


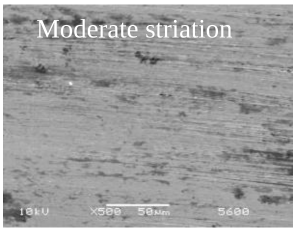
Figure 4. Influence of Process Parameters on S/N ratio of CoF for SiC-DSS reinforced surface.

3.4 Worn Surface Analysis

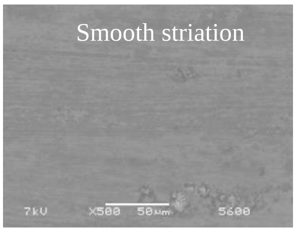
After performing a reciprocating wear test, the worn surface of the sample was examined under scanning electron microscopy to assess the wear mechanism of the SiC-DSS reinforced surface. The SEM micrograph taken is presented in Figure 5(a) to 5(i). Based on the result, the experimental number 3 exhibited a smooth appearance due to high hardness and lowest wear rate on this sample. It is demonstrated that SiC particles embedded in DSS surface has strongly bonded with substrate material and improved the wear resistance. As a result, the hard surface layer formed in the SiC-DSS reinforced surface did not easily pull out from the surface during wear reciprocating. Similar observation was found by Bello et al., [16] on the low alloy steel preplaced with TiC particles. Meanwhile, the experimental number 1 and 4 experienced a mild striation due to second and third highest hardness in this sample, respectively.

Furthermore, if the comparison is made of the results in experimental number 9, the worn surface exhibited a grooves and severe wear. This result contributes from the lowest hardness in this sample compared to another experimental run. Besides of that, the experimental run number 5 and 7 demonstrate the severe striation due to lower hardness on these samples. In addition, the reduction of hardness increasing the contact between intercourse surfaces and promoting deep penetration of the alumina ceramic ball in the steel matrix.

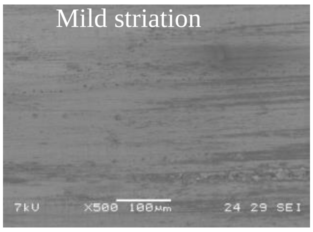
(a) Exp. no. 1



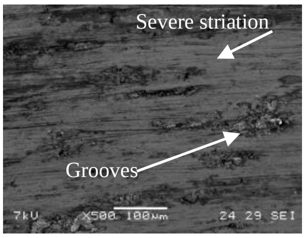
(b) Exp. no. 2



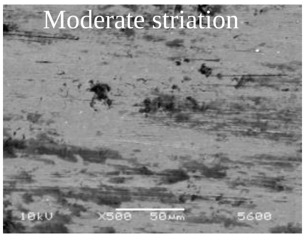
(c) Exp. no. 3 (best)



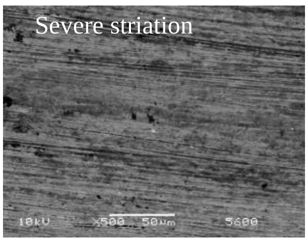
(d) Exp. no. 4



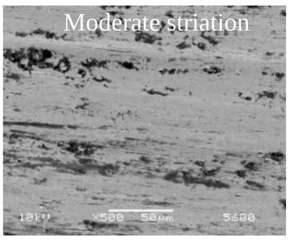
(e) Exp.no. 5



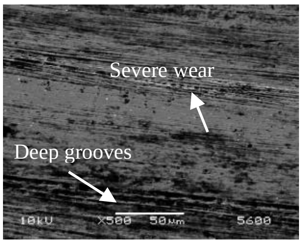
(f) Exp. no. 6



(g) Exp.no. 7



(h) Exp. no. 8



(i) Exp. no. 9 (worst)

Figure 5. SEM image of the SiC-DSS reinforced surface attained for experiment number 1 to 9.

4. CONCLUSION

The following findings can be taken from the current investigation.

a) SiC ceramic particles deposited on DSS surface and melted using TIG torch techniques has reinforced the surface properties of DSS.
b) The optimum process parameters using Taguchi method has successfully developed.
   1. Surface hardness and wear rate - 80 A of current, 20 V of voltage, 1.0 mm/sec of transverse speed and 25 L/min of argon flow rate
   2. Coefficient of friction - 80 A of current, 20 V of voltage, 1.0 mm/sec of transverse speed and 20 L/min of argon flow rate
c) The main worn surface mechanism for SiC-DSS reinforced surface exhibited mild striation for the best sample in experiment no. 3. Meanwhile, the grooves with severe striation for the worst sample in experiment no. 9.
d) The most influence of the process parameters for SiC-DSS reinforced surface for surface hardness and wear behavior is similar with current is prominent parameter. Meanwhile, transverse speed is a non-significant parameter and least effect on the of SiC-DSS reinforced surface.

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