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Tribological properties of surface modified Ti-6Al-4V alloy under lubricated condition using Taguchi approach

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KEYWORD

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ABSTRACT

Surface modification technique is important to enhance the tribological properties of titanium alloy grade 5 (Ti-6Al-4V). One of the surface melting techniques is tungsten inert gas (TIG) torch welding to produce similar results to the costly high power laser technique. The substrate alloy was preplaced with silicon carbide (SiC) powder and then melted using tungsten inert gas (TIG) torch surface melting technique. The process parameters of the surface melting technique are current, voltage, travel speed and SiC powder size. The process optimization was carried out to obtain the desired quality characteristics of the SiC coated surface using Taguchi method in the Minitab version 17 software. The results showed that the significant improvement of hardness and better wear rate performance. The maximum hardness increased until 482.3 Hv compared to substrate material of 152.8 Hv. The lowest result of the SiC modified titanium alloy for wear rate is 0.1711 mm3/Nm and coefficient of friction is 0.39. It is found that the voltage and SiC powder sizes play important role on the hardness, wear resistance and coefficient of friction of the modified titanium alloy surface layer.

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1.0 INTRODUCTION

Currently, surface hard coating technique has been widely used in various sectors such as in the automotive, aerospace industry and also in the biomedical application. The engineering components in these fields normally operated in extreme condition where heat, friction and dynamic motion works together. As consequence, the materials will quickly damage and the component life span will be shorter. Surface coating can improve the tribological properties of a material by enhancing its near-surface hardness, wear resistance and reducing its coefficient of friction. Composite coatings can be done by surface melting techniques such as laser surface melting and tungsten inert gas (TIG) torch surface melting technique. Surface engineering using TIG torch melting of duplex stainless steel surface by incorporation of ceramic particles produced better hardness than substrate hardness. The increment of hardness of this modified layer contributed from dendritic microstructure that strongly bonded to the substrate material (Lailatul and Maleque, 2017).Surface hard coating is considered as a part of surface engineering as it involves creating a new or modified surface phase in the solid surface (Ramnarayan, 2014). Surface engineering is performed on various engineering parts to change their thin near-surface layer while maintaining its core properties. Previous research by Kaleem et al. (2016) investigated the cemented tungsten carbide (WC-Co) substrates using hot filament chemical vapor deposition (CVD) – diamond coatings. The finding showed that average coefficient of friction of the coated surface was decreased from ~ 0.37 to 0.32. The hardness results of coated surface increased until 50 GPa compared to substrate material of 18 GPa.

Titanium alloy is widely used in engineering industries such as aeronautical, chemical, petrochemical and marine applications. Ti-6Al-4V is a titanium alloy grade 5 with good mechanical properties, excellent corrosion resistance and having low density (Dewidar, 2006). However, the grade 5 titanium alloys have poor tribological properties since it has poor wear resistance, lower hardness and high coefficient of friction (Boyer et al., 1994). Therefore, the improvement of these properties is required to increase the performance of the engineering components and to extend their life service without any un-anticipated failure. One of the methods to meet this requirement is to perform the hard surface coating onto this alloy using ceramic particles on the surface melted with TIG torch technique.

TIG torch melting with different process parameters and phases characterization of surface modified layer was done by previous researchers (Ulutan et al., 2010; Pasupathy and Ravisankar, 2013). It is proven that the process parameters play significant role influencing tribological performance of the developed composite coating. The parameters that need to be controlled are current, supply voltage, travelling speed, arc gap length, electrode size, argon gas flow rate and preplaced powder content and composition (Peng, 2012a; Maleque et al., 2013; Mridha et al., 2015). Previous research work by Maleque and Adeleke (2013) studied the surface alloying of commercial purity titanium (CP-Ti) using preplaced Fe-C-Si powder by TIG technique. The surface modified CP-Ti alloy exhibited hardness value ranging from 600 Hv to 800 Hv which was 3 times higher than substrate material.

To have the desired quality characteristic from the TIG surface modification technique, a proper experimental tool should be used to determine the significant factors for optimization. In the past years, Taguchi design have been used widely where it measures the robustness to identify the control factors that can decrease the variability of certain process by minimizing the noise factor which is the uncontrollable factors. Taguchi method determines the minimal number of trials for process optimization as compared to the full factorial design. Taguchi approach is a powerful tool for experimental design because it provides a simple, efficient, and systematic approach for optimizing wear performance, quality, and cost (Peng, 2012b). In order to develop composite-alloyed surfaces with optimal coating characteristics based on the interaction of the process variables, the statistical method is required for high-energy efficient process. One of the popular techniques of process optimization is the Taguchi method. This method is a powerful tool to design of high quality systems. It offers a systematic approach, simple and efficient to optimize design for performance, quality and cost.

Taguchi parameter design is able to optimize the performance characteristics through the setting of design parameters and reduce the sensitivity of the system performance to source of variation. It also enables a comprehensive understanding of the individual and combined parameter from a minimum number of simulation trials (Karna et al., 2012; Arkadeb et al., 2016). This procedure has been successfully implemented in previous study done by Bello et al. (2015) and analyzed the hardness behavior of TIG surface modified low alloy steel based on Taguchi approach. Based on the experimental result, the hardness improved until achieved 808.53 Hv compared to substrate material of 300 Hv. From the Taguchi S/N ratio response analysis, the effects of voltage and speed were found to be more significant for the hardness performance. The application of taguchi approach was found a successful method to optimize the coating performance characteristics. Other finding by Maleque et al. (2017) revealed that the application of Taguchi approach was feasible method to optimize the tribological behavior of SiC embedded on low alloy steel. Based on the analysis, the highest influence parameter on the tribological performance is argon gas flow rate.

In terms of lubrication used in the industry, the biodiesel has been used in recent years as an alternative source of energy to replace petroleum. Petroleum has been used widely in vehicles or machines but the sources of the fossil fuel is depleting. This is because petroleum is a non-renewable source. Petroleum plays a major role to the air pollution since it releases carbon monoxide and carbon dioxide to the environments. In contrast, biodiesel is a renewable source and it does not bring harms to the environment. However, the presence of fatty acid and free water in biodiesel can leads to corrosion (Fazal et al. 2013). Hence, Ti-6Al-4V is used to study its interaction based on its tribo-corrosion behavior in a biodiesel environment with SiC powder preplaced on its surface. Other finding by Farhanah and Syahrullail (2016) were investigated the refined lubrication of refined, bleached and deodorized (RBD) palm stearin as an alternative lubrication. The results revealed that the RBD lubricant has improved the coefficient friction and anti-wear resistance.

The main aim of this study is to improve the tribological properties of grade 5 (Ti-6Al-4V) under lubricated condition based on Taguchi approach. The substrate alloy was preplaced with silicon carbide (SiC) powder and tungsten inert gas (TIG) torch surface melting technique was applied for composite coating on Ti-6Al-4V alloy. The Taguchi experimental design of L9 orthogonal array was used to analyze the effect of main TIG process parameters on the wear rate, coefficient of friction and surface hardness of the TIG-processed SiC coated Ti-6Al-4V under lubricated condition. Furthermore, optimum setting of parameters for the TIG surface melting technique was determined.

2.0 MATERIALS AND METHODS

2.1 Materials and powder preplacement

The material used for this study is titanium alloy grade 5 (Ti-6Al-4V). The chemical composition of the substrate is shown in Table 1 (Pala et al., 2015). The substrate material was machined and cut to dimension of 17 mm x 40 mm x 15 mm using EDM wire cut. The surface of the material was abrasively ground to a surface roughness of about R_a = 0.4 µm using SiC emery paper. The surface of material was rinsed with acetone and ethanol to remove impurities or contamination such as dust, oxide layer and grease. The SiC powder preplacement with different sizes of 20, 40 and 60 µm was used for surface modification. The SiC powder was mixed with a small amount of polyvinyl acetate (PVA) binder with 0.5 mL for 2 mg of powder and agitated to form a paste with the aid of distilled water and alcohol. The addition of binder is to keep the powder on the surface under the flow of the shielding gas. The pre-placed samples were then dried in the oven at 60ºC for 30 minutes to remove the moisture.

Table 1: Chemical composition of Ti-6Al-4V alloy.

Titanium grade	**Chemical composition (%)**							
Ti-6Al-4V	Ti	Al	V	Fe	O	C	N	H
Grade 5	89.464	6.08	4.02	0.22	0.18	0.02	0.01	0.0053

2.2 Design of experiment

Taguchi design refers to experimental design as "off-line quality control" because it is a method of ensuring good performance in the design stage of products or processes. The input variables of the surface coating technique for TIG torch melting are current, electrode travel speed, voltage and silicon carbide powder size. Each independent variable was set at three levels. Since there are 4 factors with 3 levels each, L9 orthogonal array is the suitable taguchi design to be used. This method is used in designing and analyzing the effect of TIG process parameters on the wear rate, coefficient of friction (CoF) and hardness performance of the TIG-processed SiC reinforced composite coated Ti-6Al-4V under lubricated condition. The design matrix is conducted as per experimental design tabulated in Table 3 whereby each column represents a process parameter and while row represents test condition corresponding to a combination of parameter levels. The multi-parametric response is presented in terms of wear rate, coefficient of friction and hardness.

Table 2: Levels of the parameter used in the experiment.

Control factor	**Levels**		
	1	**2**	**3**
Current (A)	70	80	90
Speed (mm/s)	1.0	1.5	2.0
Voltage (V)	20	25	30
Silicon carbide powder sizes (µm)	20	40	60

Table 3: Experimental design matrix for TIG torch process for SiC coating.

Experimental runs	**Current (A)**	**Speed (mm/s)**	**Voltage (V)**	**SiC powder sizes(µm)**
1	70	1.0	20	20
2	70	1.5	25	40
3	70	2.0	30	60
4	80	1.0	25	60
5	80	1.5	30	20
6	80	2.0	20	40
7	90	1.0	30	40
8	90	1.5	20	60
9	90	2.0	25	20

2.3 SiC coating on Ti-6Al-4V alloy using TIG melting

TIG torch technique was conducted to melt the SiC preplaced on the surface of Ti-6Al-4V. The melting of the material was carried out under a Miller TIG arc cladding machine (Model: Telwin TIG 165) to produce a series of track layers. During the cladding, the pure argon was used as shielding gas to protect the molten pool from excessive oxidation. A tungsten thoriated electrode with diameter of 3.2 mm was used to strike an arc between electrode and preplaced surface. The heat input of the TIG torch depends on the current and voltage used and it was calculated using the following formula (Dyuti et al., 2010);

$$\text{Heat input} \quad = \frac{0.48 \times current(I) \times voltage(V)}{Electrode\ tranverse\ speed\ (mm/s)} \tag{1}$$

2.4 Lubricated wear testing

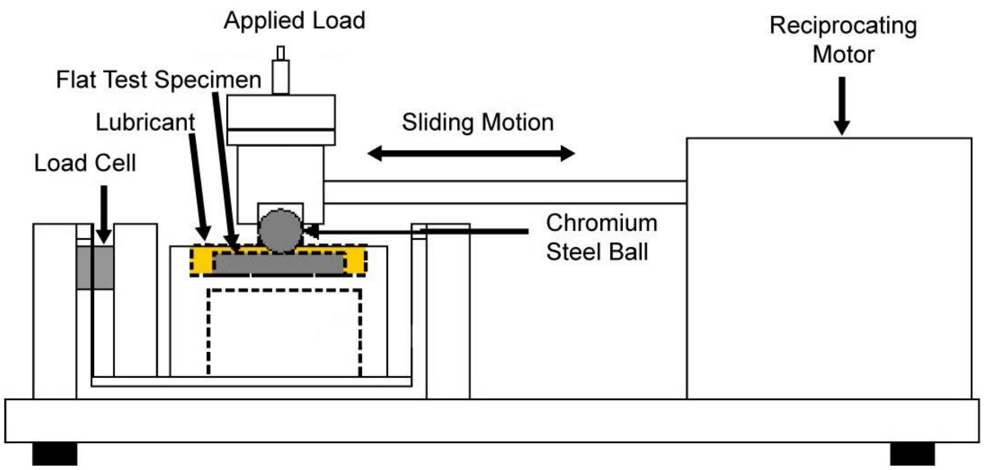
For wear test, the modified layer was cut using a wire EDM machine and the surface was ground and polished until became flat. The wear testing under lubricated condition with jatropha bio-diesel was conducted using ball-on-disc reciprocating tribometer with constant load of 30 N and frequency of 10Hz for 30 minutes. The schematic diagram of reciprocating wear test machine and sample configuration is illustrated in Fig. 1a and Fig. 1b respectively. The counterpart material was chromium steel ball with diameter of 6 mm. The wear rate was calculated using equation 2 and the coefficient of friction is obtained from the software (Katoch et al., 2016).

$$\text{Wear rate, } W_r = \frac{\Delta w}{2\pi rnt} \tag{2}$$

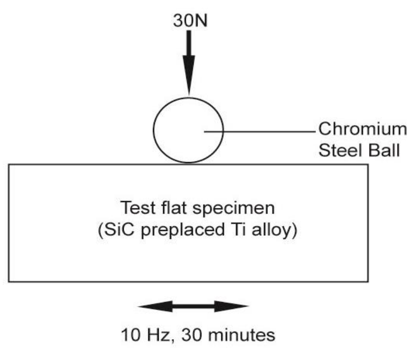
Where *Wr* is the wear rate in terms of volume loss, *Δw* is weight loss, *n* is revolution per minute, r is the radius of ball distance from the centre of the steel disc and *t* is the sliding time. The test was conducted with biodiesel as lubricant and the properties of the lubricant showed in Table 4. After wear test, the worn track of the samples was observed under optical microscope to inspect the wear behavior of SiC coated Ti-6Al-4V.

Table 4: Properties of jatropha bio-diesel lubricant.

Density, g/cm^2	0.92
Viscosity (cSt)	5.2
Flash point, °C	240
Acidic value (mg KOH/g)	>12.4



(a)



(b)

Figure 1: Schematic diagram of (a) reciprocating wear test machine (b) sample configuration of wear test.

2.5 Vickers micro hardness

Vickers micro-hardness was conducted to determine the hardness across the melt pools. After the surface melting process, the composite coated Ti-alloy surface hardness was measured using Wilson Wolpert Vickers microhardness which located in Surface Engineering Lab, IIUM. The transverse section of the composite coated was cut using EDM wire cut. The micro-hardness test was performed with load of 500gf and dwelling time of 10 seconds. The measurement was taken at a depth of 200 μm from the top surface of the composite coated melt pool towards substrate material. The test results were calculated based on the average of five indentations from each specimen.

3.0 RESULTS AND DISCUSSION

3.1 Wear rate analysis

The wear rate of silicon carbide reinforced composite coated Ti-6Al-4V alloy for each experimental run of L9 orthogonal array is listed in Table 5. The best wear performance among the 9 experiments is experiment 4 which the wear rate obtained is 0.1711 mm3/ Nm. This is associated with the high hardness of this sample due to SiC embedded in the titanium alloy matrix. The wear rate is found to be the highest for experiment 1 which the value is 0.4212 mm3/ Nm. This is related to the lower hardness value obtained for this sample as can be seen in Table 9. In Taguchi method, the wear rate of the TIG processed coating is analyzed with S/N ratio using the smaller the better criterion. The signal-to-noise ratio is calculated in decibel scale (dB) using equation 3 (Yang and Tarng, 1998).

$$\frac{\mathrm{S}}{\mathrm{N}} = -10 \log \frac{1}{n}\left(\sum Y^2\right) \tag{3}$$

Where Y is the experimental data and n is the number of experiment. The wear rate value and the corresponding S/N ratio obtained for each of L9 experiment are shows in Table 3. The computation and analysis of S/N ratio is done using Minitab 17 statistical software package.

Table 5: Experimental results for wear rate with S/N ratio.

Experiment runs	Wear rate (mm^3/Nm)	S/N ratio (dB)
1	0.4212	-12.490
2	0.1975	-5.911
3	0.3160	-9.994
4	0.1711	-4.665
5	0.4081	-12.215
6	0.3028	-9.623
7	0.2370	-7.495
8	0.3555	-11.017
9	0.3291	-10.347

The S/N response analysis is obtained from the experiment results by calculating the average of S/N ratio for each level of selected process factor or parameter. The mean responses for S/N ratio and main effect plot of wear rate are shown in Table 6 and Figure 2 respectively. From the obtained result, the rank ‘1’ and rank ‘2’ indicates that the voltage and SiC powder size have a stronger effect on the TIG process. Rank ‘3’ in the same table shows that welding speed has a strong effect on the process followed by Rank ‘4’ which means that welding current has the minimum effect on the process.

Table 6: Mean responses for S/N ratio of wear rate.

Levels	Current (A)	Speed (mm/s)	Voltage (V)	SiC powder size (μm)
1	-9.465	-8.217	-11.043	-11.684
2	-8.834	-9.714	-6.974	-7.676
3	-9.619	-9.988	-9.901	-8.559
Delta	0.785	1.771	4.069	4.007
Rank	4	3	1	2

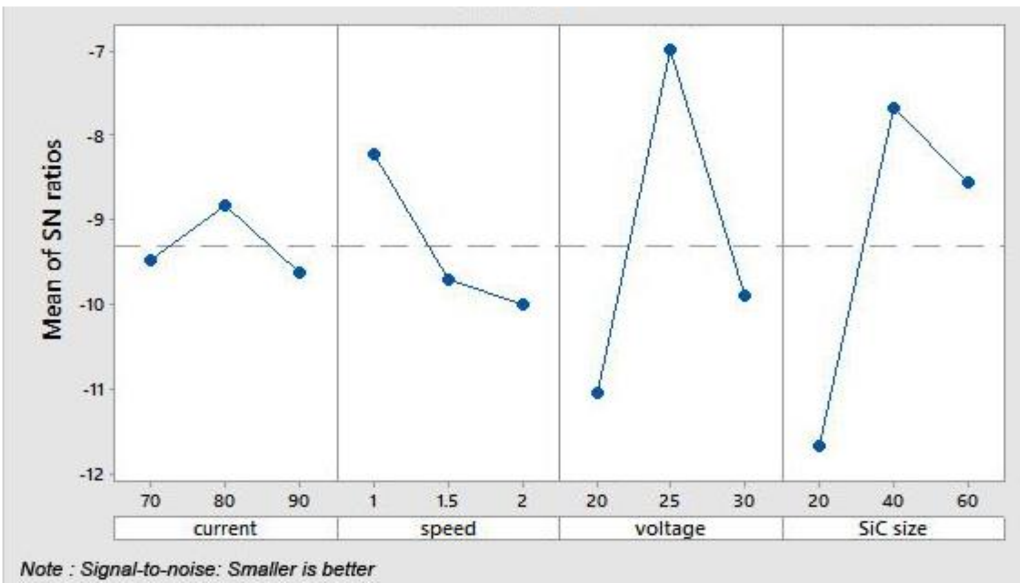


Figure 2: Main effect plot for the wear rate of SiC coated Ti-6Al-4V.

From the main effect plot in Figure 3, the inclination of the plot is used to determine the significance of each parameter. The parameter with the highest inclination line has most effect on the wear rate of the material. Hence, the optimum value to obtain the minimum wear rate of SiC composite coated Ti-alloy was at current level of 80A, speed of 1.0 mm/s, voltage of 25V and SiC powder size of 40 μm.

3.2 Coefficient of friction (CoF) analysis

The CoF value and corresponding S/N ratio for all experimental runs is shown in Table 7. The mean responses of S/N ratio and main effect plot for CoF are shown in Table 8 and Figure 3 respectively. The ranking which gives the order of importance of the TIG process factors indicates that CoF is influenced by welding voltage, SiC powder size, speed and current in that order. Interestingly, this trend is similar to what was obtained for wear rate and hardness response in this study. The best CoF performance obtained is experiment 4 where the CoF value is 0.39033. The lower CoF produced is related to the higher hardness value and higher distribution of carbides in the modified surface layer. As a result, the load transferred to the surface of the sample is reduced during wear sliding. This is similar to the previous finding by Maleque and Adeleke (2015) where the ceramic reinforcement reduced the CoF of the samples because of the higher degree of hardness. The optimum combination of process parameters is current level of 80A, speed of 2 mm/s, voltage of 25 V and SiC powder size of 40 μm.

Table 7: Experimental results for CoF with S/N ratio.

Experiment runs	**Coefficient of friction**	**S/N ratio (dB)**
1	0.76740	-17.7004
2	0.44203	-12.9090
3	0.53409	-14.5523
4	0.39033	-11.8286
5	0.75285	-17.5342
6	0.48091	-13.6413
7	0.47353	-13.5069
8	0.87323	-18.8226
9	0.51043	-14.1587

Table 8: Mean responses for S/N ratio of CoF.

Levels	**Current (A)**	**Speed (mm/s)**	**Voltage (V)**	**SiC powder sizes (μm)**
1	-15.05	-14.35	-16.72	-16.46
2	-14.33	-16.42	-12.97	-13.35
3	-15.50	-14.12	-15.20	-15.07
Delta	1.16	2.30	3.76	3.11
Rank	4	3	1	2

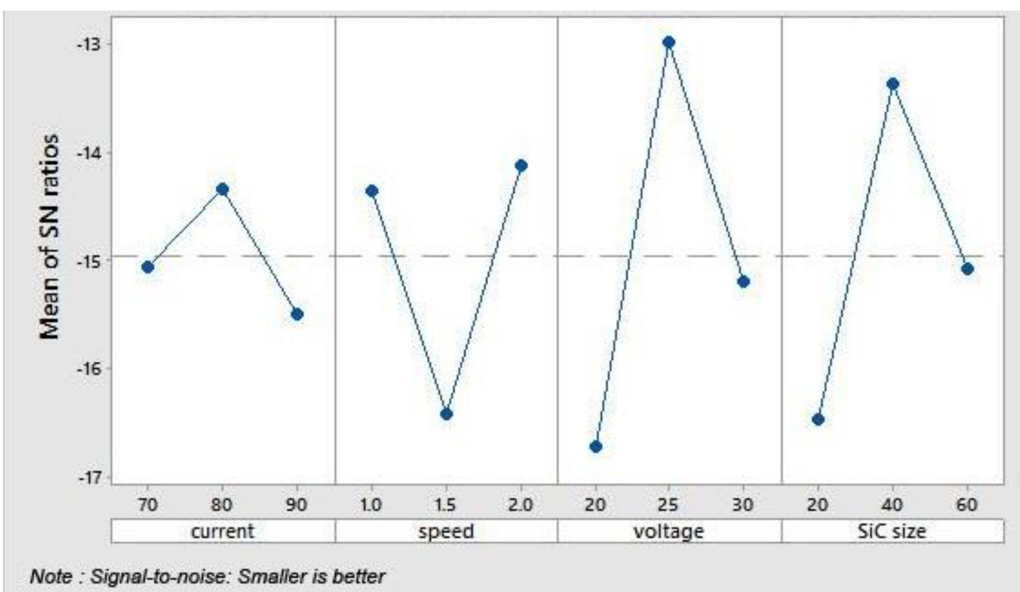


Figure 3: Main effect plot for CoF of SiC coated Ti-6Al-4V.

3.3 Vickers micro hardness

The surface hardness of substrate material (Ti-6Al-4V) is 152.8 $Hv_{0.5kgf}$. As can be seen in Table 9, the surface hardness value for all of the experimental runs showed a great increment after the

TIG processed SiC coating. Other researchers also reported similar results where it is found that SiC dispersed composite layer can enhance the surface of the modified layer in terms of hardness and wear characteristics (Buytoz, 2006; Mridha and Baker, 2007). The higher degree of hardness according to Lailatul and Maleque (2017) is related to the complete melting of SiC particles and the carbide precipitation. The lower hardness obtained might be associated with the dissolution of the SiC reinforcement from vigorous stirring of the fluid melt at greater heat input during the cladding process. The optimal experimental condition is measured by the maximum S/N ratio because of the variability of the characteristics is inversely proportional to S/N ratio. The main purpose is to improve the hardness of the composite coated Ti-alloy, therefore, the S/N ratios were calculated using the "larger the better" method as shown as below (Yang and Tarng, 1998):

$$\text{S/N (THB)} \quad = -10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)dB \tag{4}$$

where, n = number of experimental run in a trial/row,
y_i= hardness value obtained for each respective trial/row.
The S/N ratio hardness values obtained using above formula for this experiment was tabulated in Table 9.

Table 9: Vickers hardness value and their S/N ratio.

Experiment runs	**Vickers hardness (HV)**	**S/N ratio (dB)**
1	332.2	50.4280
2	475.4	53.5412
3	470.6	53.4530
4	492.3	53.8446
5	370.0	51.3640
6	458.3	53.2230
7	396.6	51.9671
8	390.2	51.8257
9	452.4	53.1105

Table 10: Mean response for S/N ratio of surface hardness.

Levels	**Current (A)**	**Speed (mm/s)**	**Voltage (V)**	**SiC powder sizes (μm)**
1	52.47	52.08	51.83	51.63
2	52.81	52.24	53.50	52.91
3	52.30	53.26	52.26	53.04
Delta	0.51	1.18	**1.67**	1.41
Rank	4	3	**1**	**2**

The single-response values in Table 10 shows that the voltage applied for the welding process is the most significant factor to have a high value of surface hardness. This is followed by other factors which are SiC powder size, electrode travel speed and current.

Figure 4 shows the main effects for S/N ratios for surface hardness of TIG processed SiC coating on Ti-6Al-4V alloy. Based on the maximization principle, it was found that the means and

S/N ratio values that the optimal level setting for surface hardness is current of 80A, speed of 2.0 mm/s, voltage of 25V and SiC powder sizes of 60 μm.

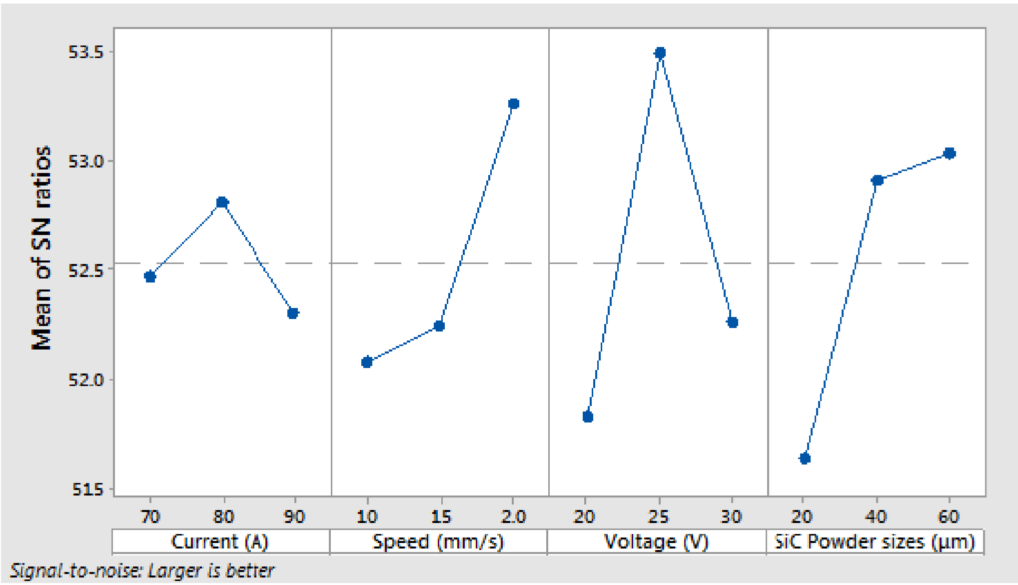


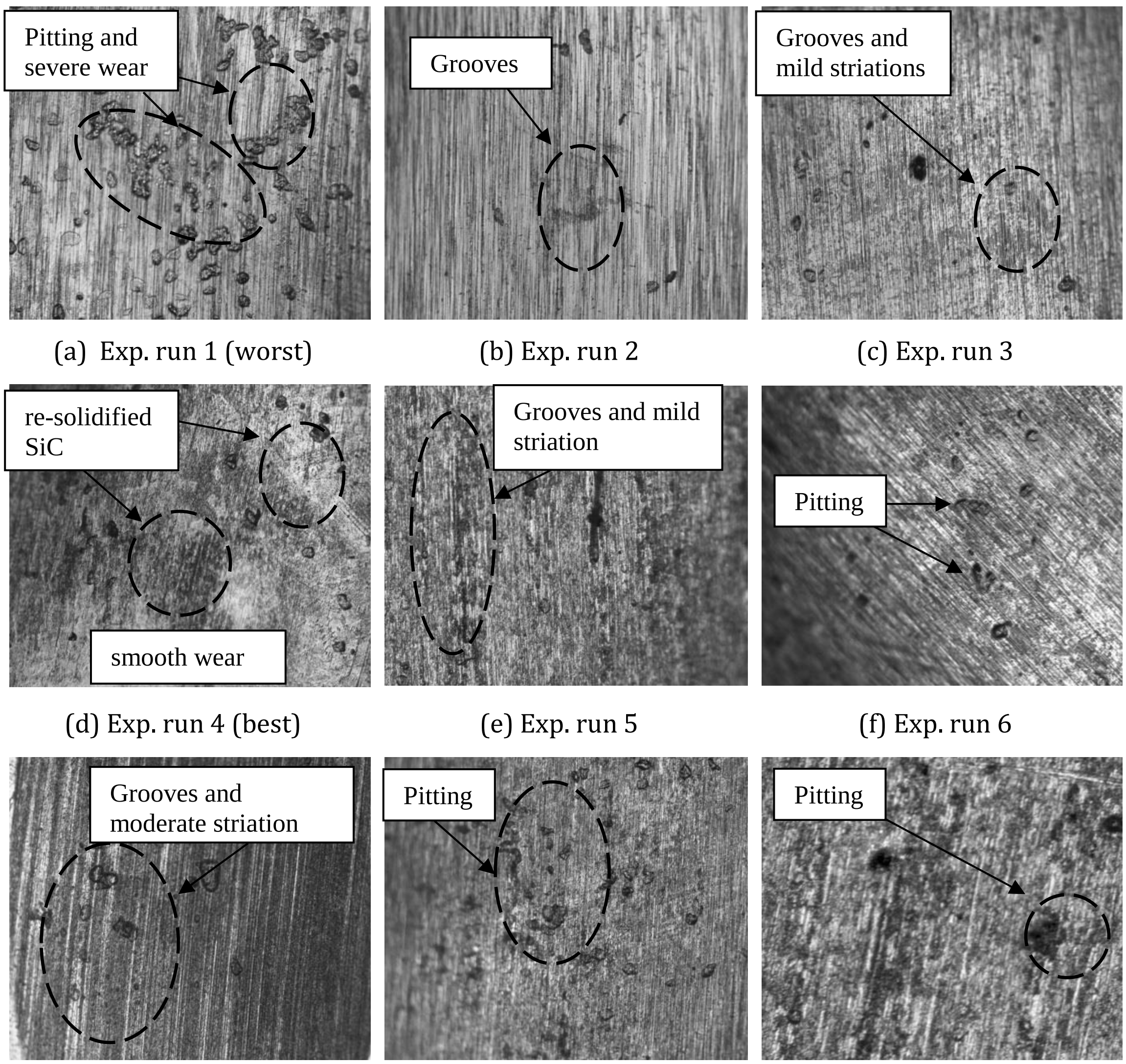
Figure 4: Main effect plots for surface hardness of SiC coated Ti-6Al-4V.

3.4 Wear mechanism

The worn surfaces of the samples after reciprocating wear test were observed under optical microscope to analyze the wear behavior. The image taken can be seen in Figure 5(a) to 5(i). The irregular piting formed for experimental run 1,4,6,8 and 9 whereas the other samples are observed as longitudinal grooves and mild striations on their surface. The presence of grooves shows the occurrence of abrasive wear in which there are micro-cutting and micro-ploughing observed. Similar work by Sakiru and Shahjahan (2015) observed that the titanium alloy grade 2 (CP-Ti) coated with SiC subjected to dry wear test were almost free from obvious pitting formation. However, this phenomenon is not observed with the titanium alloy in the present study.

For modified surface layer in Figure 5(d), it is showed that the incorporation of SiC ceramic particles has improved the wear resistance with smooth worn surface. It proved that SiC phases are strongly bonded to the substrate material. However, the experimental run 1 in Figure 5(a) exhibited severe worn surface and this is might be due to lower hardness and less bonding between SiC and substrate material; hence the ceramic particles easily pull out from the surface matrix during reciprocating wear.

The SiC coated Ti-6Al-4V was subjected to lubricated wear test and after some time, it can be seen that there are obvious pitting formations on the worn surface. These indicate the corrosion-wear phenomenon that occurred on the solid surface during the wear test. In other words, the formation of the tribo-corrosion of the SiC coated Ti-6Al-4V is confirmed. However, there are good effects of using the biodesel as lubricant. The wear rates and coefficient of friction in the present study shows significantly better with lower values as compared to the titanium alloy that is subjected to the dry tribological test. Biodiesel can reduce the scuffling period and hence decrease the wear rate and coefficient friction of the samples. This is most possibly because of their fatty acid components, oxygenated moieties and unsaturated molecules (Fazal et al., 2013).



(a) Exp. run 1 (worst) (b) Exp. run 2 (c) Exp. run 3

(d) Exp. run 4 (best) (e) Exp. run 5 (f) Exp. run 6

(g) Exp. run 7 (h) Exp. run 8 (i) Exp. run 9

Figure 5: Wear worn surface morphologies of SiC coated Ti-alloy for different exp. runs. Test conditions: chromium steel ball; 30 minutes; 10 Hz.

CONCLUSIONS

From the present study, the following conclusions can be drawn;

(a) SiC preplaced Ti-6Al-4V alloy was melted using TIG surface technique for composite coating.
(b) The optimum process parameters for wear rate are 80A of current, 1 mm/s of travel speed, 25 V of voltage and 40 μm of SiC powder size, coefficient of friction are 80A of current, 2 mm/s of travel speed, 25 V of voltage and 40 μm of SiC powder size and surface hardness are 80A of current, 2 mm/s of travel speed, 25 V of voltage and 60 μm of SiC powder size.
(c) The hardness increased 2.5 times higher compared to substrate material hardness.
(d) The main wear mechanism under lubricated condition exhibited abrasive type of wear with grooves and pitting formation on the composite surface.
(e) The influence of the process parameter for SiC reinforced composite coated Ti-6Al-4V for wear rate and friction behavior almost similar. However, TIG voltage and SiC powder sizes are the prominent factor in this investigation for the development of composite coating.

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