TAGUCHI OPTIMIZATION OF HARDNESS PROPERTIES AND STUDY THE EFFECT ON MICROSTRUCTURAL FEATURES OF SiC REINFORCED COMPOSITE COATING DUPLEX STAINLESS STEEL

Lailatul Harina Paijan[1,*], Abd Maleque[2], Mohd Hadzley Abu Bakar[1],Mohd Basri Ali[1], Mohd Fauzi Mamat[1], Mohd Hairizal Osman[1] and Mohd Rashidi Asari[3]

[1]Department of Industrial Technology, Faculty of Mechanical and Manufacturing Engineering Technology, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.
[2]Department of Manufacturing and Materials Engineering, Kuliyyah of Engineering, International Islamic University Malaysia, P.O. Box 10, 50728 Gombak, Kuala Lumpur, Malaysia.
[3]Perusahaan Otomobil Nasional Sdn Bhd, Mukim Hulu Bernam Timur, Daerah Batang Padang, 35950 Behrang Stesen, Tanjung Malim, Perak, Malaysia

*lailatulharina@utem.edu.my

Abstract. Durability and strength of the materials engineering are major properties that might lead to component failure or diminish their operational especially in tribological applications. One approach to avoid this limitation is to perform a surface modification to protect the material from degradation. Hardness is one of the important metallurgical tests for any metallic materials which may result from different manufacturing and treatment processes. In the present work, the hardness behavior of silicon carbide (SiC) reinforced composite coated duplex stainless steel fabricated using tungsten inert gas (TIG) torch cladding was investigated. The process parameters of TIG torch technique were optimized using Taguchi L9 orthogonal array design of experiments. The important parameters that directly related to the energy input on the surface melting during cladding are taken into consideration such as welding current, voltage, transverse speed and argon flow rate. The hardness was evaluated using Vickers micro-hardness tester and the microstructural features were analyzed using scanning electron microscopy and the composition of sample was investigated using energy dispersive x-ray. Based on the Taguchi's experimental design analysis, the results showed that the TIG cladding parameters of 80 A of current, 20 V of voltage, 1.0 mm s^{-1} welding transverse speed and 25 $Lmin^{-1}$ argon flow rate are the optimal values for hardness performance of the reinforced composite coating with hardness value of 1000 Hv. The microstructural features revealed that the dendrite is formed due to incorporation of SiC ceramic particles on duplex stainless steel (DSS) via TIG torch melting process and this microstructure is responsible to the increment of hardness.

Keywords: Optimization, hardness, duplex stainless steel, microstructural, TIG torch

Article Info

Received 27th November 2022
Accepted 18th December 2022
Published 23rd December 2022

ISSN: 1823-7010, eISSN: 2600-7444

Introduction

TIG torch is a cladding technique to melt the surface of the material. To produce a heat, the electric arc between weld pool and non-consumable tungsten electrode need to be created. This electric arc is produced by the current through inert gas such as argon, helium, nitrogen or CO_2 gaseous. The purpose of this inert gas is to protect the solidifying weld metal, electrode and molten metal from contamination by the atmosphere as shielding gas [1]. The surface modification using TIG torch process is a new technique to produce surface with flexible, simple, low cost establishment and good metallurgical bonding to the base material [2-4].

With this approach, the ceramic particle of preferable composition is homogeneously preplaced onto the surface of substrate materials prior to TIG torch cladding. The purpose of this technique is to improve hardness and wear resistance of the material without vanish the properties of bulk material [5]. In past research, surface modification techniques have been widely used with a different method to increase hardness and wear behavior of steel surfaces such as TIG torch [2,3], electron beams [6], laser cladding [7] and plasma cladding [8,9]. Most of the outcome provides an improvement on the material surface properties. Maleque et al. [10] investigated the TIG torch surface cladding on AISI 4340 coated with TiC to improve the hardness and wear behavior. The incorporation of TiC into the steel has increased the surface hardness about five times higher compared than uncoated materials. The highest hardness attained until 996 Hv. In a previous work by Mridha et al. [3] has studied the TiC incorporated composite layers on AISI 4340 alloy steel by TIG melting cladding gave the maximum hardness of 1200 Hv than those obtained to substrate material of 300 Hv. Past research by Buytoz [11] demonstrated that the incorporation of SiC into SAE 1020 carbon steel using TIG torch cladding process has increased the surface hardness of the material between 744 and 1135 Hv.

In recent years, DSS has been widely used in petrochemical, chemical, construction, automotive, and aerospace industries that provides great performance and have a capability to replace austenitic stainless steel [12]. DSS is a material contains of equal proportion of ferrite and austenite. These two phases are correlated well with the heat treatment process and chemical composition. It gives a combination property of mechanical strength, ductility, good corrosion resistance, abrasion resistance and good weldability [13]. However, DSS having some weaknesses on hardness and wear problem which limits their use in most tribological application. Due to this, surface modification of this material is required to overcome the problem. TIG torch process is a possible technique to improve hardness and wear problem for this material. Previous study by Sahu et al. [14] revealed that the TIG process with preplaced TiC-Ni wire coating has improved the hardness of AISI 304 stainless steel plate about 500 to 1500 Hv. The sliding SiC abrasive wear of TiC-Ni clad layer showed the enhancement of wear resistance by 50 % compared to substrate material.

The statistical method to optimize the process parameters for ceramic particles preplacement on surface material and TIG torch is required in this work. One of the powerful methods for process optimization is the Taguchi method. With this approach, it provides a structured method, simple and efficient method to optimize quality, cost and performance. The advantage of using Taguchi method is able to offers a comprehensive understanding of the individual and combined parameters from a minimum numbers of experiments [15]. Due to excellent performance of this method, the Taguchi method is one of the popular techniques used by previous researcher on the process optimization and has been successfully implemented. Maleque et al. [4] analyzed the modified surface layer on titanium material using reciprocation wear test under lubricated condition using Taguchi approach. It is observed that the voltage and SiC particle size gave a strong effect to the improvement on hardness, wear resistance and coefficient of friction of the modified titanium surface layer.

The objective of this study is to determine the optimal settings of TIG torch process parameter using Taguchi's experimental design method approach. Orthogonal arrays of Taguchi method using signal-to-noise (S/N) ratio is employed to find the optimal levels and analyze the effect of the TIG torch cladding process parameters on hardness performance of DSS. The microstructural features were investigated to observe the increment of hardness on the surface modified layer.

Materials and Methods

Duplex stainless steel with grade 2205 plate (30 mm x 50 mm x 10 mm) was used as substrate material in this study. The surface of the substrate material was ground using silicon emery paper from 120, 240, 400, 800, 1200, 2400 and finally 4000 grit size. After that, the sample thoroughly cleaned in acetone and running water to remove all contaminants such as oxide layers and grease. In this study, the ceramic particle of 20 µm of SiC was used as coating powder and reinforcement of the composite coated DSS. The SEM image of the SiC particles is shown in Figure 1. Prior to TIG torch cladding process, the SiC was preplaced on the surface of substrate material. The coating powder weighed at the proportion of 0.5 mg mm^{-2} was mixed with PVA (polyvinyl acetate) and addition of alcohol and water to form a paste. The purpose of the binder of PVA was to prevent the coating powder blowing away during melting process [16]. The powder preplaced surface was then dried in an oven for 1 hour at 80 °C to remove the moisture during preplacement process.

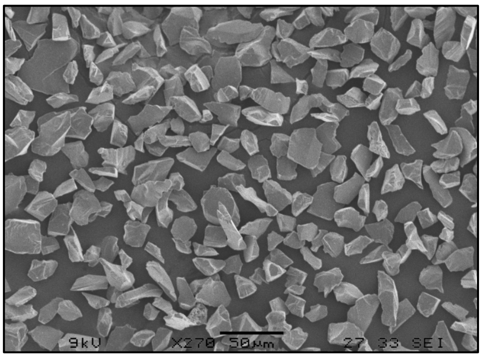

Figure 1: SEM image of 20 µm SiC ceramic particles

In order to melt the preplaced surface coating and substrate DSS, the TIG torch process with various process parameters were used in this study. To protect the molten pool from excessive oxidation, the argon gas was used for shielding gas. A tungsten electrode with diameter 3.2 mm was used to strike an arc between preplaced surface coating and electrode. The heat input of the TIG torch cladding depends on the process parameters used and it was calculated using equation 1 [17].The schematic diagram of the TIG torch machine experimental setup is shown in Figure 2.

$$\text{Heat input (HI)} = \frac{0.48 \text{ x current (A) x voltage (V)}}{\text{Transverse speed (mm/s)}} \quad (1)$$

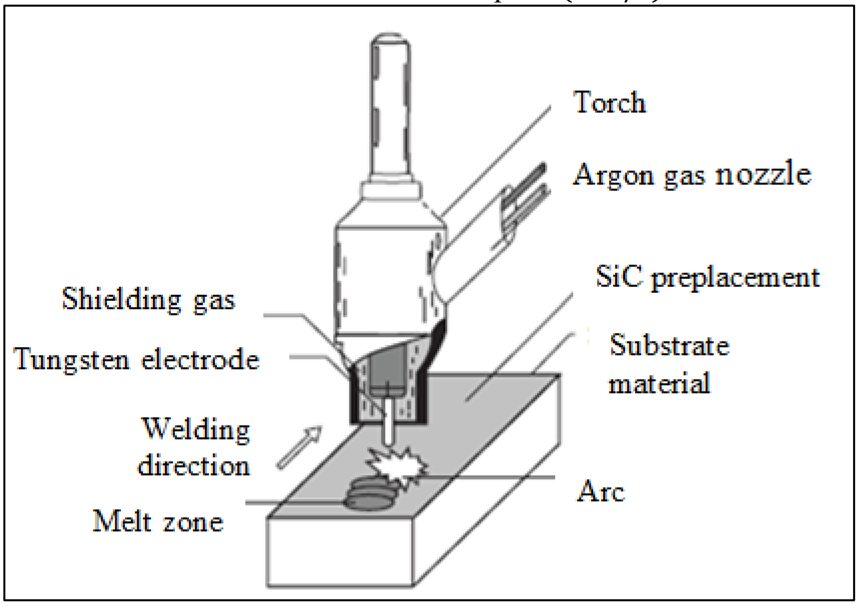

Figure 2: Schematic diagram of the TIG torch machine experimental setup

The main objective in the Taguchi method is to design robust systems that reliable under uncontrollable conditions [18]. Taguchi's technique is used for optimizing the process parameters of a single response optimization. A single setting of process parameters can provide single quality characteristic. In this process, the experimental results were transformed into signal-to-noise (S/N) ratio. The computation and analysis of S/N ratio is done using Minitab (version 17) statistical software package. The quality characteristics measured from the S/N ratio that indicates the magnitude of desirable (signal) and undesirable (noise) response characteristics. The best factor (parameter) combination is determined using single response optimization process by analyzing the effect of individual factor on the observed responses. A robust (insensitive) system will have a high S/N ratio representing the optimum parameter for each factor. The effect of TIG process parameters which are voltage current, transverse speed and argon flow rate are chosen in this study. To optimize the TIG process parameters, the Taguchi orthogonal array of L9 (3^4) was applied with nine experiments conducted at different parameters, with four factors and three levels. In this investigation, the response variable is the surface hardness. Each of experimental trial was conducted for three times. The factor level and their corresponding response are listed in Table 1.

After the TIG torch cladding completed, the sample was allowed to cool down at room temperature. Then, the electrical discharge machine (EDM) was used to cut the transverse section of the composite coated sample. The cross section of the specimen was ground using emery paper and then etched with Kalling’s reagent to reveal the microstructure. Then, the Vickers microhardness test (model Wilson Wolpert) was conducted according to ASTM E384 with 500 gf load and 10 seconds indentation time. The measurement was taken from a cross-sectioned sample near to the surface of the composite layer. The test results were calculated based on the average of three indentations from each sample. On the microstructural features observation, the microstructure of the cross-sectioned samples was examined under scanning electron microscopy (model JEOL JSM 5600). The SEM machine is installed with software of JSM 5600. Meanwhile, the composite coating composition of the samples was investigated using energy dispersive x-ray (EDX) analyzer (model ISIS).

Results and Discussion

Hardness Test Result and Taguchi Array Analysis

The optimal experimental condition is measured by the maximum signal to noise ratio (S/N ratio). Since the larger hardness is preferred in this study, the larger-the-better (LTB) formulation is chosen. The equation to calculate S/N ratios for LTB characteristics (in decibel) is shown in equation 2;

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

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 was tabulated in Table 1.

Table 1: Experimental layout using L9 (3^4) orthogonal array

Exp. No.	Current:A (A)	Voltage:B (V)	Transverse speed:C (mm/s)	Argon flow rate:D (L/min)	Hardness (Hv)	S/N ratio (dB)
1	80	20	1	15	922.7	59.3012
2	80	30	1.5	20	833.6	58.4192
3	**80**	**40**	**2**	**25**	**1000.0 (best sample)**	**60.0000**
4	90	20	1.5	25	922.7	59.3012
5	90	30	2	15	659.3	56.3817
6	90	40	1	20	898.0	59.0655
7	**100**	**20**	**2**	**20**	**701.9 (moderate sample)**	**56.9255**
8	100	30	1	25	701.9	54.2277
9	**100**	**40**	**1.5**	**15**	**514.5 (worst sample)**	**54.2277**

The surface hardness with the average mean and S/N ratios of all levels is tabulated in Table 2. The results revealed that the current values (A) have the strong influence on hardness performance followed by gas flow rate (D) and voltage (B). Transverse speed (D) is non-significant parameter and least influence on the hardness values of composite coated DSS. The optimum arrangement becomes A1B1C1D3 that means welding current is 80 A

(A1), voltage is 20 V (B1), transverse speed is 1.0 mm/s (C1) and argon flow rate is 25 L/min (D3). Figure 3 shows the main effects for S/N ratios for surface hardness of composite coated DSS.

Table 2: S/N response table for surface hardness

Levels	A (current)	B (voltage)	C (transverse speed)	D
1	**59.24**	58.51	58.50	56.64
2	58.25	57.32	**57.32**	**58.14**
3	56.10	**57.76**	57.77	58.82
Delta	3.14	1.19	1.19	2.18
Rank	1	3	4	2

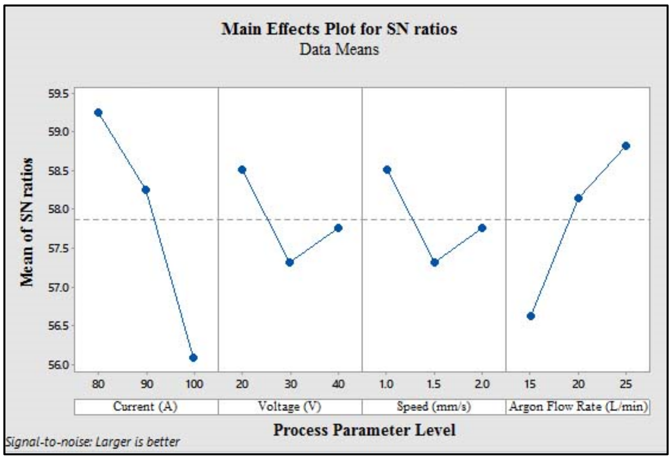

Figure 3: Main effect plots for surface hardness of TIG composite coated DSS

Confirmation Test

After the optimum level of TIG process parameters in performance characteristics identified, a verification test needs to be done in order to evaluate the accuracy of the analysis. The verification test was required because the optimum combination parameters and their levels did not correspond to any experiment of the orthogonal array. The optimum process parameters of composite coating were verified using the predicted S/N ratio and confirmatory experimental results. The condition of A1B1C1D3 of new parameter combination of TIG cladding was treated as confirmatory run. The results revealed that the experimental results gave the surface hardness of 1032 Hv while the prediction results gave the surface hardness of 1104 Hv. It can be seen from Table 3, the difference between experimental and prediction of S/N ratio is only 2.0017 dB. This demonstrates that the experimental value of hardness is very close to the estimated value, as the error is only 1.076 %. This result is in close agreement with previous studies by Satish and Krivinas [19] who found out that the error percentage for hardness between experimental value and predicted value was 5 %.

Table 3: Results of the confirmatory experiment using the optimal process parameters

	Level	Surface hardness	
		Mean value (Hv)	**S/N ratio (dB)**
Experiment	A1B1C1D3	1032	60.818
Prediction	A1B1C3D3	1104	61.480
Difference	-	72	2.0017
Error (%)	-	6.52	1.076

Microstructural Features

Among nine experimental runs, it is proved that experiment number 3, 7 and 9 consider as best, moderate and worst sample of TIG torch operating condition to the increment of hardness, respectively. Therefore, the surface morphology for these samples is further discussed to observe the microstructural features of the reinforced composite coated DSS. The image from cross-sectional view of the samples for experiment number 3, 7 and 9 is shown in Figure 4. The melt depth of the sample is 1180, 1540 and 1010 µm for sample 3, 7 and 9, respectively.

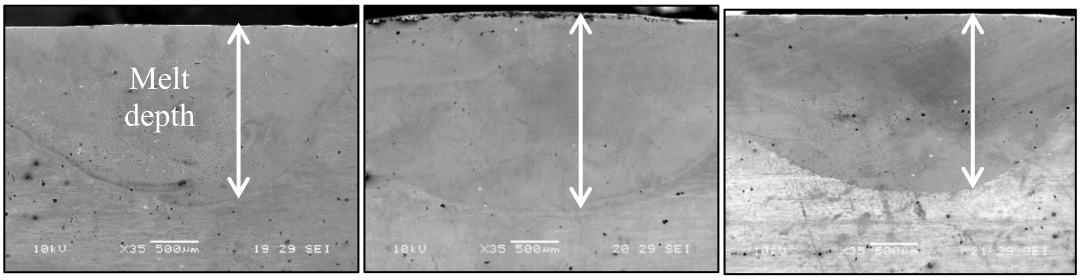

Figure 4: Cross-sectional view of composite coated DSS for; (a) sample 3 at 768 J/mm, (b) sample 7 at 1440 J/mm and (c) sample 9 at 480 J/mm

In Figure 5(a), it can be seen that the best sample in sample 3 revealed the formation of dendrite with densely high population in this region. The dark phase is SiC ceramic particles and the light phase is iron matrix. The formation of dendrites is responsible for the increment of hardness with complete melting of SiC. This phenomenon could be explained due to sufficient heat input of 768 J/mm and high dilution of substrate and SiC ceramic particles in molten metal. The similar justification is given by Mridha & Dyuti [20] for carbon steel substrate with reinforced titanium powder under TIG torch melting. The large difference of the melting points of iron and SiC ceramic particles dissolution resulted in the development of dendrite structure [11].

In Figure 5(b), the melt microstructures consist of partially dissolved and complete dissolved of SiC ceramic particles with arrayed dendrite formation in sample 7. This sample melted at heat input of 1440 J/mm. At higher heat input of TIG torch cladding process, the melt pool experienced longer solidification time due to higher dissolution of SiC ceramic particle and substrate material. It can be seen that dendrite structure became thicker due to high fluidity in the melted layer leads to greater convection force that may accelerate the dissolution of SiC ceramic particles. The dendrite population in the melted layer also reduces compared to sample 3 processed at heat input of 768 J/mm.

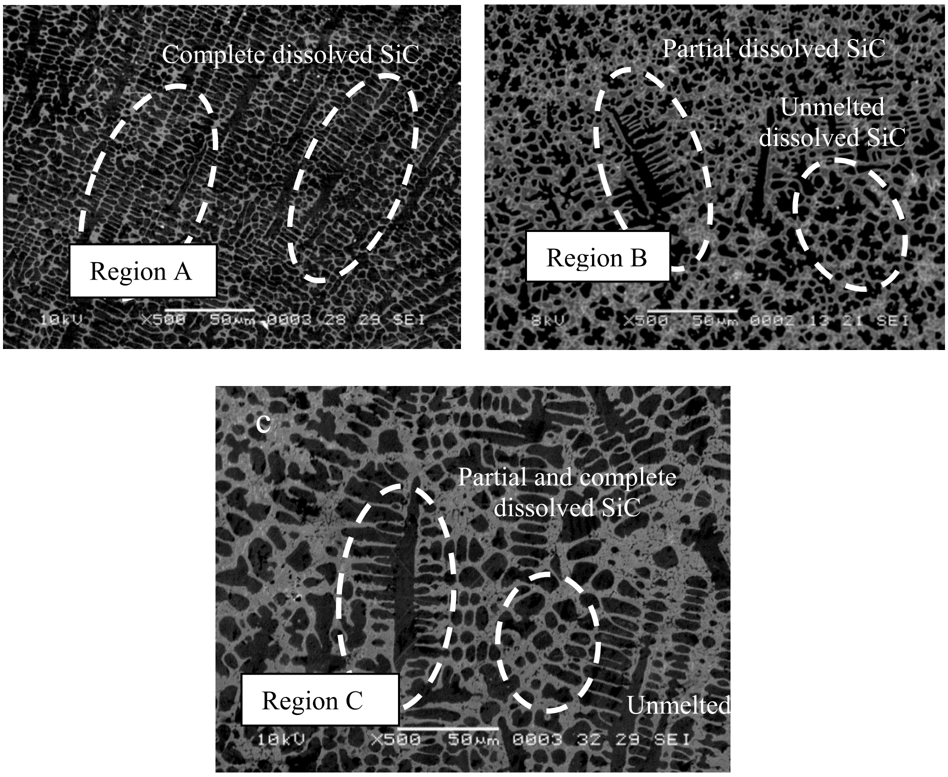

Figure 5: SEM micrographs of TIG torch melted DSS using 20 µm SiC particle size using heat input for; (a) sample 3 at 768 J/mm, (b) sample 7 at 1440 J/mm and (c) sample 9 at 480 J/mm

When TIG torch process was performed at lower heat input of 480 J/mm, it can be found that the un-melted SiC was observed in the TIG melted layer in samples 9, as can be seen in Figure 5(c). The SiC ceramic particles did not melt appropriately thus experienced the variation of population of unmelted, partial and complete dissolve of SiC particles. Moreover, the melt fluid becomes thick and caused the melting to freeze within very short time which retarded the possibility of SiC particles to be precipitated in the melted layer completely [21].

The precipitated microstructure into dendritic formation (Figure 5(a) to (c)) is confirmed as SiC based on evidence from EDX result in Figure 6 contains of silicon and carbon. The EDX spectra on the incorporated 20 µm SiC particle size in DSS for sample 3 (region A) is shown in Figure 6(a). It was found that the element of silicon (Si) and carbon (C) are detected which indicating the existence of SiC ceramic particles in the TIG melted layer DSS with the contents of 9.05 % and 12.03 %, respectively. This is due to the heat input of 768 J/mm promotes higher substrate dilution leading to high amount of SiC particles dissolved in the liquid melt pool.

In Figure 6(b), the EDX spectra (region B) revealed lower percentage of silicon (Si) with 7.94 % and carbon (C) of 7.60 % due to higher heat input of 1440 J/mm in sample 7. However, at region C in Figure 6(c), sample 9 (region C) exhibited lower percentage of Si with 5.94 % and C with 7.59 % due to lower heat input of 480 J/mm, leads to lower dilution of SiC particles dissolved in the liquid metal.

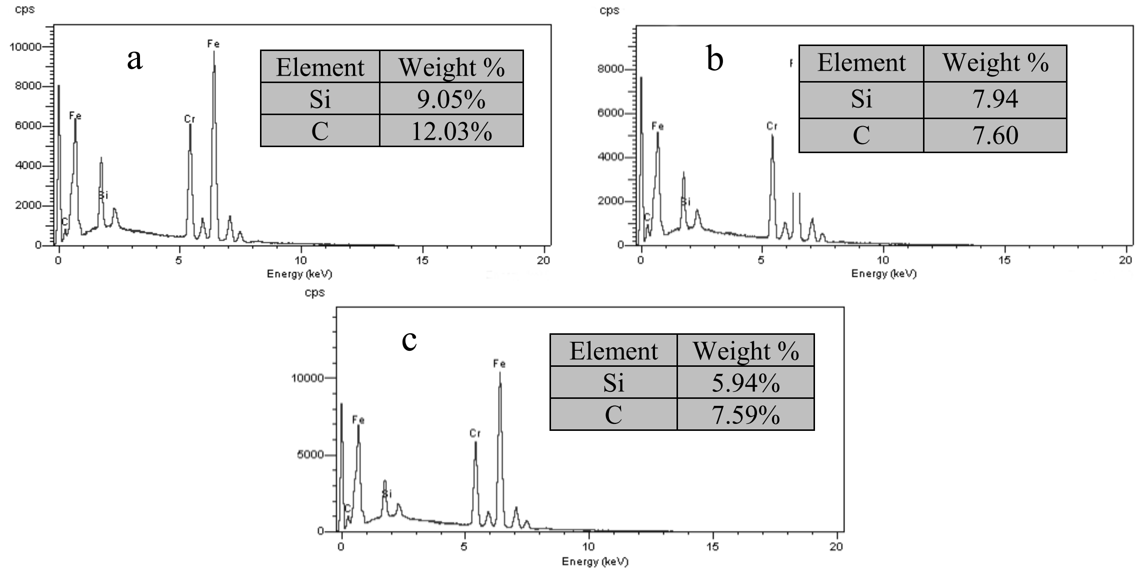

Figure 6: EDX spectra of TIG melted layer DSS for 20 µm SiC particles within dendritic region as shown in Figure 5 indicating region A, B and C; (a) sample 3 at 768 J/mm, (b) sample 7 at 1440 J/mm and (c) sample 9 at 480 J/mm

Conclusions

The discussion of the implementation of the Taguchi method to investigate the parameter optimization and TIG torch melting process variables and the effects of microstructural features on the hardness increment was done successfully. The SiC composite coated DSS was developed using TIG surface modification technique through the design of experiments and statistical approach. It is found that the optimum TIG torch parameters with SiC ceramic particles preplacement on the surface hardness is at the current level of 80 A current, voltage of 20 V, transverse speed of 1.0 mm/s and argon flow rate of 25 L/min. The current and gas flow rate have the strongest influence on the surface hardness of SiC composite coated DSS. The confirmation test analysis showed that the predicted and experimental results were found to be very close. It can be concluded that the microstructural features of the reinforced composite coated DSS revealed the formation of dendrites microstructure with complete, partial and un-melted dissolved SiC that leads to the increment of hardness due to sufficient heat input and high dilution of SiC and substrate DSS.

Acknowledgements

The financial support for this research was provided by Short Term Grant UTeM 2022 (S01895-PJP/2022/FTKMP) and Ministry of Higher Education Malaysia for Fundamental Research Grant Scheme (FRGS) with Project Code: FRGS/1/2015/TK05/UIAM/01/1. Authors also are grateful to the Universiti Teknikal Malaysia Melaka and International Islamic University Malaysia for the support that made this study possible.

Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare

Compliance with Ethical Standards

The work is compliant with ethical standards

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