Melting of SiC powders preplaced duplex stainless steel using TIG welding

M A Maleque1 and M Afiq1
1Department of Manufacturing and Material Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia

Email: maleque@iium.edu.my

Abstract: TIG torch welding technique is a conventional melting technique for the cladding of metallic materials. Duplex stainless steels (DSS) show decrease in performance under aggressive environment which may lead to unanticipated failure due to poor surface properties. In this research, surface modification is done by using TIG torch method where silicon carbide (SiC) particles are fused into DSS substrate in order to form a new intermetallic compound at the surface. The effect of particle size, feed rate of SiC preplacement, energy input and shielding gas flow rate on surface topography, microstructure, microstructure and hardness are investigated. Deepest melt pool (1.237 mm) is produced via TIG torch with highest energy input of 1080 J/mm. Observations of surface topography shows rippling marks which confirms that re-solidification process has taken place. Melt microstructure consist of dendritic and globular carbides precipitate as well as partially melted silicon carbides (SiC) particles. Micro hardness recorded at value ranging from 316 HV0.5 to 1277 HV0.5 which shows increment from base hardness of 260 HV0.5kgf. The analyzed result showed that incorporation of silicon carbide particles via TIG Torch method increase the hardness of DSS.

1. Introduction
Duplex stainless steel has been used in various applications such as high pressure valves and heat exchangers due to its high strength and stress corrosion resistance. Despite many of duplex stainless steel advantages, there are also some limitations in which prohibit the usage of duplex stainless steel in certain application. The usage of duplex stainless steel in corrosive environment and aggressive environment will lead to the material’s failure due to combined action of wear and corrosion simultaneously [1]. In order to improve properties of duplex stainless steels, surface modification technique can be done taking into account corrosion are phenomenon occurring at the surface of the components. Also, in service components or parts do not solely rely on the inherent properties of their bulk material but also on the properties of their surface. Surface modification is a method involving all processes that are used in order to improve surface properties of engineering materials. Surface modification can be done by transforming surface microstructure or by developing a new intermetallic compound layer on a material’s surface in which the process done does not affect properties of bulk material [2].

In recent studies, TIG Torch has gained more interest as this method has been considered as cheaper alternatives of lasers treatments [3, 4]. This method can be used to incorporate ceramic reinforcement materials which enhance mechanical properties of substrate materials via surface
melting. Surface melting method is used because of its ability to eliminate interfacial incompatibility by creating thermodynamically stable reinforcements based on their nucleation from the substrate material. Idris et al. [5] investigated the TiC composite coating on AISI 4340 using TIG torch method. Other finding by Adeleke et al. [3] studied the Fe-C-Si coatings on CP-Ti melted under TIG torch techniques. The hardness value increased with the value of 800 Hv compared to 200 Hv of substrate material. Silicon carbide is chemically inert to acids and alkalis in temperature range up to 800 °C. In the range of 1200°C and 1900°C in air, silicon carbide has the ability to form a protective layer of silicon oxide [6]. Silicon carbide also has high chemical and wear resistance due to its ability to resist degradation under physical condition. This material is also one of the semiconductor materials that have the ability to withstand high temperature electronic and electro-optic application. These properties of silicon carbide make them suitable candidates for surface modifications of stainless steel.

Yet, no study has been carried out to melt the SiC powder with DSS using TIG technique for surface modification. Therefore, the purpose of this work is to investigate the microstructure and hardness behavior of DSS surface with SiC powder preplacement using TIG torch technique melted at energy input of 480, 768 and 1728 J/mm.

2. Experimental procedures
S31803 duplex stainless steel was used as a substrate with dimension of 33 mm x 50 mm x 10 mm. The surfaces of the samples are milled and ground in order to obtain flat surfaces for silicon carbide preplacement. SiC particles of size 20 µm, 40 µm and 60 µm were used as reinforcement materials. SiC content of 0.5, 1.0 and 1.5 mg/mm² were preplaced on the surfaces by mixing with PVA (polyvinyl acetate) binder. Powder preplaced samples were then dried in Contherm oven at 800°C for 1 hour to ensure removal of moisture.

Conventional TIG Torch welding equipment is used to melt surface of powder preplaced samples in order to produce SiC reinforced composite coating samples. Two types of layers were produced viz. single track and overlapped tracks welding. Tungsten electrode was used to generate an arc between the electrode and the powder preplaced samples using Argon as shielding gas at flow rate of 15, 20 and 25 L/min. During the process, current and voltage were set at constant of 80 A and 30 V while traversing speed of 1.0 mm/s, 1.5 mm/s and 2.0 mm/s were used. The parameters used in TIG Torch are shown in table 1.

| No. of DSS sample | Preplacement Rate (mg/mm²) | SiC particles size (um) | Traveling speed (mm/s) | Heat Input (J/mm) | Gas Flow Rate (L/min) |
|-------------------|---------------------------|------------------------|-----------------------|------------------|----------------------|
| Sample 1          | 0.5                       | 60                     | 1                     | 1080             | 25                   |
| Sample 2          | 0.5                       | 40                     | 1.5                   | 720              | 20                   |
| Sample 3          | 0.5                       | 20                     | 2                     | 540              | 15                   |
| Sample 4          | 1.0                       | 40                     | 1                     | 1080             | 15                   |
| Sample 5          | 1.0                       | 20                     | 1.5                   | 720              | 25                   |
| Sample 6          | 1.0                       | 60                     | 2                     | 540              | 20                   |
| Sample 7          | 1.5                       | 20                     | 1                     | 1080             | 20                   |
| Sample 8          | 1.5                       | 60                     | 1.5                   | 720              | 15                   |
| Sample 9          | 1.5                       | 40                     | 2                     | 540              | 25                   |

A Miller TIG torch source attached with a semi-automatic traversing arm was used for melting purpose. The direct current electrode negative (DCEN) mode was used and a 3.2 mm diameter
tungsten electrode was used to strike an arc between the electrode and the workpiece in pure Argon atmosphere to prevent excessive oxidation [3]. Minitab 17 software was used to determine the no. of experiments to be conducted with the predetermined variables and their levels [5]. The optimum setting is the parameter combination, which has the highest S/N ratio [7]. The experiments have been carried out as per Taguchi’s L16 orthogonal array (OA) design.

After welding, a complete cross section of the weldments composed of the parent plate and TIG melted surface layer was removed transverse to the welding direction to produce specimens for microstructural examination and hardness measurements. All specimens were ground on silicon carbide “wet” papers from P320 to P1200 grade and polished sequentially on diamond wheels using 3, 1 and 0.25 μm grades. The weld metal microstructure was revealed by using 2% Nital. The microstructure was evaluated using a JMS 5600 field emission scanning electron microscope.

3. Results and Discussion

3.1 Surface Topography

The topographies of the TIG melted surface layer produced were observed under FESEM and shown in figure 1. Rippling marks can be seen at surface of all samples which proved that re-solidification has occurred at region near substrate surface. Ripple marks are produced when there is a difference between re-solidification rates. Area behind the electrode is usually re-solidify first compared to area being melted.

Surface layer produced with heat input of 1080 J/mm² at SiC content of 0.5 mg/mm² (sample 1) shows relatively smooth surface texture (weld track) and contain more ripple marks compared to other samples. This is because higher heat input and lower preplacement rate increased melt fluidity and prolong solidification time during TIG Torch process [8]. On the other hand, sample produced at heat input of 540 J/mm² and preplacement rate of 1.5 mg/mm² (sample 9) demonstrate less smooth
surface texture (weld track) with less number of ripples. This is due to its high viscosity melt produced during TIG Torch process [3].

Unmelted SiC particles can be observed on surface of sample 3 and sample 6. Unmelted particles is caused by lower heat input used during TIG Torch process due to increased welding speed of glazing. Other features that can be observed are the presence of porosities and cracks. Porosities occurred when entrapped gas escaped from the melt surface during resolidification due to high viscosity of the melt produced. Pores is observed when heat input used is low thus producing viscous melt. Upon, resolidification, the viscous melt is unable to fill the void left by escaping gas thus producing pores on the surface of the samples [6].

3.2 Melt pool dimension
The melt pool width and depth for all samples are shown in table 2. The largest melt pool dimension was observed in sample 1 which is produced with preplacement rate of 0.5 mg/mm² and heat input at 1080 J/mm². Smallest melt pool was observed in sample 9 which is produced with preplacement rate of 1.5 mg/mm² and heat input at 540 J/mm².

| No. of DSS sample | Width of surface layer (mm) | Depth of surface layer (mm) |
|-------------------|-----------------------------|-----------------------------|
| Sample 1          | 6.14                        | 1.24                        |
| Sample 1          | 5.47                        | 0.99                        |
| Sample 3          | 5.17                        | 0.68                        |
| Sample 4          | 5.83                        | 1.2                         |
| Sample 5          | 5.15                        | 0.85                        |
| Sample 6          | 4.87                        | 0.79                        |
| Sample 7          | 5.46                        | 1.12                        |
| Sample 8          | 5.04                        | 0.76                        |
| Sample 9          | 4.68                        | 0.62                        |

Table 2. Melt pool dimension of TIG melted layer of DSS.

It can be seen that at the same preplacement rate of 0.5 mg/mm², surface layer produced at heat input of 1080 J/mm has larger melt dimension compared to samples produced at 720 J/mm and 540 J/mm. Higher heat input produced higher width and depth of the melt pool as can be seen in sample 1 compared to sample 2 and sample 3. This is because of high heat input resulted higher temperature of melt during TIG welding. This higher temperature melt has lower solidification rate which assists the melt to move towards the substrate thus producing larger melt pool [5].

Melt pool of sample produced at 0.5 mg/mm² is larger than sample produced at 1.0 mg/mm² and 1.5 mg/mm² at the same heat input of 1080 J/mm. Sample 1 (which is produced at highest heat lowest preplacement rate) shows largest melt pool dimension when compared to sample 4 and sample 7. It can be seen that increasing preplacement rate during the process at the same energy input affects the dimension of melt pool. This is because lower preplacement rate (i.e. loer SiC) produced content on the surface. Lower content of SiC particles on the surface prolong heat dissipation time from the base metal thus producing larger depth melt pool.

3.3 Hardness measurement
The new surface layer samples were cut along the cross-section for micro hardness measurements and reading was taken along the melt pool region. The hardness of substrate material was 260 HV0.5kgf. Hardness profiles for each sample was constructed by plotting Vickers hardness measurements against
depth at which measurement was taken. Hardness profiles of the samples are shown in table 3 after measuring maximum hardness for each sample from the average of five readings.

Table 3. Maximum Micro Hardness of the Samples.

| No. of DSS sample | Width of surface layer (mm) |
|-------------------|-----------------------------|
| Sample 1          | 316.8                       |
| Sample 1          | 614.3                       |
| Sample 3          | 899.8                       |
| Sample 4          | 864.5                       |
| Sample 5          | 661.1                       |
| Sample 6          | 1126                        |
| Sample 7          | 830.4                       |
| Sample 8          | 1250                        |
| Sample 9          | 1263                        |

From table 3, it can be seen that there is an increment in hardness value of all SiC reinforced composite coating (surface layered) sample compared to hardness value of substrate sample. Sample 8 shows the highest value of hardness recorded in this experiment with the value of 1277 HV$_{0.5}$ while sample 1 shows the lowest value of hardness with the value of 316.8 HV$_{0.5}$. Sample 8 (with preplacement rate of 1.5 mg/mm$^2$) shows highest hardness value of 1250 HV$_{0.5}$ while sample 2 (with 0.5 mg/mm$^2$) at the same heat input shows lower hardness value of 614.3 HV$_{0.5}$. Higher content of SiC preplaced on the sample results from the higher amount of SiC which precipitates during re-solidification, hence increase the value of hardness of the DSS material.

4. Conclusion
From the present study, the following conclusions are drawn: Silicon carbide particles incorporation into duplex stainless steel can be done by using TIG Torch method. The usage of different preplacement rate, size of SiC particles, heat input and gas flow rate affect melt dimension, microstructure and hardness of the produced samples. Melt pool dimension produced with 1.5 mg/mm$^2$ preplacement rate is smaller compared to those produced with 0.5 and 1.0 mg/mm$^2$. On the other hand, heat input of 1080 J/mm produced larger melt pool dimension compared to those produced with 720 and 540 J/mm. Highest hardness recorded is 1250 HV$_{0.5}$ from the heat input of 720 J/mm with SiC content of 1.5mg/mm$^2$. The hardness development depends on the population of dendrite structures formed during TIG Torch process.

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