



Tribological properties of surface coated duplex stainless steel containing SiC ceramic particles

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KEYWORD	ABSTRACT
TIG torch surfacing Tribological properties Duplex stainless steel Wear Surface coating	<p>This paper presents an experimental investigation on the tribological properties of coated duplex stainless steel (DSS) containing SiC ceramic particles. The preplaced SiC powder with 20 μm particle size and TIG torch surfacing was conducted with energy inputs of 480, 768 and 1440 J/mm. The comparisons of the room temperature wear behavior of substrate DSS and coated SiC duplex stainless steel was carried out against alumina ceramic ball. The effects of the process parameters on the hardness and wear behavior were analyzed in this study. The coated surface of DSS produced hardness about 2~4 times higher than uncoated DSS. It was revealed that coated surface was improved significantly with lower wear weight loss and coefficient of friction (about 2 times lower) than the substrate material. The embedded SiC into the surface of steel has improved the wear behaviour of DSS. This is due to SiC dendrites structure that strongly bonded to the steel resulting the reduction of the friction between coated surface and the alumina ball. The wear worn surface was observed under SEM with a very mild abrasive wear for coated surface compared to severe abrasive wear for substrate DSS surface. The coated surface has showed lower surface roughness and wear depth penetration indicated that the presence of the SiC reduced the wear of the material.</p>

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1.0 INTRODUCTION

Duplex stainless steels (DSS) are family of grades combining good corrosion resistance with high strength and ease fabrication. The alloying elements of DSS are chromium, molybdenum, tungsten and nitrogen content that made this material resist to chloride pitting and crevice corrosion (TMR Stainless, 2009). DSS consists of mixed equal proportions of austenite and ferrite microstructure. These two phases is very dependent on their chemical composition and thermal treatment history. DSS is extensively used in heavy constructions vehicle for hydraulic pump piston and transmission gear, cargo tanks for ships and trucks, air duct incineration for power generation applications and in pressure vessel, tanks piping and heat exchangers in the chemical processing industry (Mourad et al., 2012; Wang et al., 2012). However, DSS exhibits some limitation on lower hardness and poor wear resistance which restricted their usage in most tribological application. In past research, surface modification techniques have been widely used with a different way to improve hardness and wear performance of steel surfaces such as TIG torch (Bello et al., 2015; Mridha et al., 2012), electron beams (Anath et al., 2013), laser cladding (Mourad et al., 2012), micro shoot peening (Hirai et al., 2016), chemical vapor deposition (Najar et al., 2016) and plasma cladding (Prasad et al., 2012; Zhang et al., 2011). Most of the finding gave an improvement on the surface properties of the material. However, all these techniques are expensive and time consuming. Therefore, in this study, the introduction of SiC embedded in DSS using TIG torch melting technique is a new approach, simple and cost effective.

TIG is a welding process that uses the electric arc created between non-consumable tungsten electrode and the weld pool to produce a heat. This electric arc is produced by the current through inert gas that also provides shielding gas of the electrode, molten weld pool and solidifying weld metal from contamination by the atmosphere. Normally, argon, helium or nitrogen gaseous is used for shielding gas depending on the requirements or applications (Technical sheets, 2007). TIG torch technique is one of the surface modification methods to produce surface with good metallurgical bonding to the base material with simple, flexible and low cost equipment establishment (Bello et al., 2015; Mridha et al., 2012). With this technique, the Fe-based alloy powder of desirable composition is homogeneously deposited onto the surface of substrate materials by TIG torch melting with the purpose to increase hardness and wear resistance without severe lost in the bulk material properties (Adeleke and Maleque, 2015).

In previous work by Lailatul and Maleque (2017) investigated the surface modified layer of duplex stainless steel with SiC preplacement using TIG melting technique. The results showed that re-solidified composite layer produced maximum hardness of 833.6 Hv from substrate hardness of 250 Hv for TIG processed of 768 J/mm energy input. The microstructure revealed the formation of dendrite phase due to complete melting of SiC in the modified layer that contributes to the increase of hardness of this material. Past research by Buytoz et al. (2006) revealed that the hardness of SAE 1020 carbon steel has improved by melting of SiC and substrate material using TIG torch melting technique. The average hardness of the coating layers have increased between 744 and 1135 Hv. Previous study by Sathiya et al. (2009) found that the TIG process has improved the hardness of the DSS material compared to base metal of 173 Hv. The hardness increased until 308 Hv and 325 Hv using shielding gas of argon and helium respectively.

Bello et al. (2016) analysed the characterisation of TIG-alloyed composite coatings containing TiC, TiC/hBN (hexagonal boron nitride) and TiC/ Ni-P coated hBN (Ni-P-hBN) lubricant additive. The substrate material used is AISI 4340 low alloy steel. The results indicate that the coated surface using TiC/Ni-P-hBN exhibits optimum properties of microstructural aspects, hardness and excellent tribological properties due to the enhanced wettability action of Ni-P encapsulated

hBN particles. The samples were able to withstand tribological application at 600°C. Maleque et al. (2015) investigated the wear behaviour of AISI 4340 coated with TiC produced by TIG surface melting. It is found that the microhardness profile of the coated sample showed improvement of the hardness value almost 5 times higher than substrate material. The wear test results showed that the coated sample has higher wear resistance with mild abrasion wear compared to the substrate material with severe type of abrasive wear.

The purpose of this study is to explore the possibility of producing hard surface alloyed by SiC powder preplacement and TIG torch melting on DSS material. For surface melting, the heat energy is provided by the torch arc which is maintained between the tungsten electrode and the specimen. The effects of energy heat input on hardness and wear behavior of SiC coated DSS have been studied.

2.0 MATERIALS AND METHODS

2.1 Materials

The material used for this study is duplex stainless steel (DSS) with the grade of ASTM A240 (also known as Duplex 2205). The material was cut into dimension of 50 mm x 33 mm x 10 mm. In order to remove all contaminants or impurities in form of oxide layers and grease, the surface of the substrate material was ground using silicon emery paper and thoroughly cleaned in acetone and running water. Details of the chemical composition of DSS are given in Table 1.

Table 1: Chemical composition of duplex stainless steel (ASTM A240).

Steel grade	Chemical Composition %						
	Si	Cr	Ni	Mo	Mn	S	Fe
ASTM A240	0.55	24.20	4.82	4.14	1.59	0.11	balance

2.2 SiC ceramic powder preplacement

The SiC with 20 µm of particle size was used in this study as coating powder for composite coated DSS. In order to meet this requirement, the SiC ceramic powder was preplaced on the surface of substrate material before TIG torch cladding. The SiC powder weighed of 0.5 mg/mm² was mixed with two drops of polyvinyl acetate (PVA) binder and agitated to form a paste with the aid of distilled water and one drop of alcohol. The binder of PVA acting as protection to prevent the coating powder blowing away during melting operation under the flow of shielding gas (Maleque et al., 2013). To remove the moisture, the powder preplaced surface was then dried in an oven at 80°C for 1 hour. After drying process, the sample was removed from the oven and allowed to cool down at room temperature.

2.3 Development of SiC coated DSS

TIG torch technique was conducted to melt the SiC ceramic powder preplaced surface coating. 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 3.2 mm was used to strike an arc between electrode and preplaced surface coating. A TIG 165 machine, set with heat input energy parameters and fix the gap distance of 1 mm below the electrode tip and workpiece to produce the torch arc. The single track of melt pool was conducted for hardness test and multiple

tracks, with 50% overlapping for wear test. The heat input (HI) of the TIG torch depends on the current and voltage used and it was calculated using equation 1 (Bello et al., 2016):

$$\text{Heat input (HI)} = \frac{0.48 \times \text{current} \times \text{voltage}}{\text{Electrode transverse speed}} \quad (1)$$

2.4 Vickers micro hardness

Vickers micro-hardness was conducted to determine the hardness profile across the melt pools. After surface melting process, the sample was measured for micro-hardness using Wilson Wolpert Vickers microhardness which located in Surface Engineering Lab, IIUM. The transverse section of the surface coated layer was cut using EDM wire cut. Then, the sample was ground using emery paper and polished using alumina paste to reveal the melt pool area. The Vickers micro-hardness test was performed using pyramid diamond indenter with a load of 500 gf and 10 seconds indentation delay. Hardness measurement was taken from a cross-sectioned piece of sample within the middle of the coated layer. The test results were calculated based on the average of five indentations from each specimen.

2.5 Reciprocating wear testing

For wear test, the surface coated layer of DSS samples were machined by EDM wire cut machine to the standard rectangular size of 15 mm × 15 mm × 6 mm. Prior to testing, the contacting surface (overlapping tracks) of the test samples were ground using emery paper to flatten the surface and remove any impurities of grease or debris. The weight of the sample was taken before and after wear test to evaluate the weight loss. The wear test under dry condition was conducted using ball-on-disc reciprocating tribometer with constant load of 30 N and frequency of 5 Hz for 10 minutes. The wear test was performed on the surface coated duplex stainless steel containing SiC ceramic particles with different heat inputs of TIG torch melting technique which is considered as the main wear condition of material in this investigation. The schematic diagram of reciprocating wear test machine and sample configuration are illustrated in Figure 1(a) and Figure 1(b) respectively. The counterpart material was alumina ceramic ball with diameter of 6 mm and hardness value of 2000 Hv. After wear test, the worn surface was observed under SEM to analyze the mechanism of wear. The surface roughness and wear depth also measured using surface profile-meter machine.

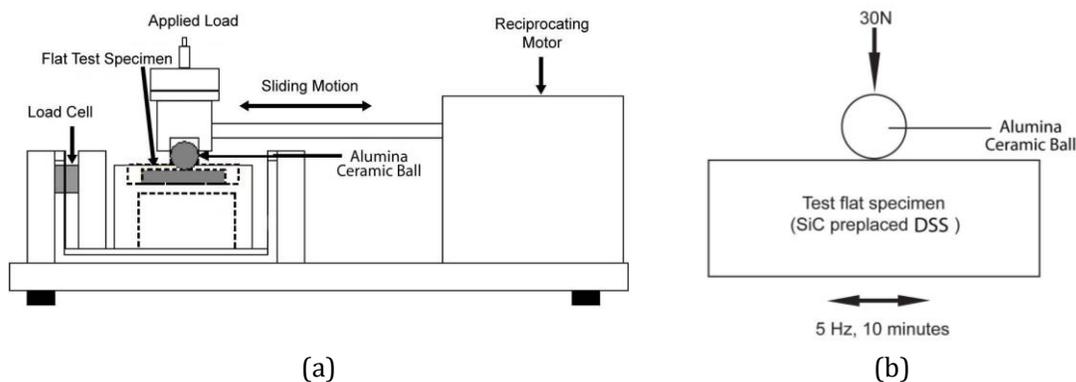


Figure 1: Schematic diagram of (a) reciprocating wear test machine and (b) sample configuration of wear test.

3.0 RESULTS AND DISCUSSION

3.1 SEM image of surface coated DSS

The microstructure of SiC coated DSS at different heat input was shown in Figure 2. Most of the tracks had produced good surface without any noticeable defects such cracks, cavities and pores. The formation of dendrite microstructure for SiC coated DSS was revealed that the TIG torch in this study was successfully melted the preplaced SiC powder mixture in DSS.

When TIG surfacing was performed at energy input of 480 J/mm, the un-melted SiC was observed in this region, as can be seen in Figure 2(a). Because of the low heat input, the melting of SiC and substrate DSS did not occurred appropriately thus produced the variation of precipitation of partial and complete dissolved of SiC particles. Other than that, at this lower energy input, the melt fluid is thick and cause the solidification time for the melt to freeze is very short and this retarded the possibility for great amount of SiC particles to be precipitated in the alloyed layer (Maleque and Adeleke, 2013).

At energy heat input of 768 J/mm, the carbide precipitation with dendrite microstructure was clearly observed with fine and densely populated at the center of the melt pool (see Figure 2(b)). This phenomenon promotes for the enhancement of hardness performance of the material as describes in previous research by Maleque et al. (2017). The complete melting of SiC in this region is due to sufficient energy input and high dilution of SiC and substrate DSS. The variation of carbide precipitation and dendrite structure is due to temperature changes in melt pool from one point to another point across the melt pool. Prior studies reported that the dendrite structure obtained due to large difference between the melting points of iron and other phases formed by SiC dissolution (Buytoz, 2006).

In Fig. 2(c), the melting processing at higher energy input of 1440 J/mm produced the high dissolution of the SiC ceramic particles for longer solidification time as reported in earlier works by Maleque et al. (2013). The high fluidity of the alloyed layer promotes the greater convection force that may accelerate the dissolution of SiC ceramic particles and forming thicker dendrite microstructures. It also shows the lesser population of dendrite formation in this coated layer and this is closely similar to previous investigation by Bello et al. (2016).

The EDX analysis of the SiC coated DSS produced at different heat input are shown in Figure 3. In Figure 3(a), the EDX analysis revealed less percentage of 7.94% and 7.60% of Si and C, respectively due to lower heat input of 480 J/mm. It can be seen that elemental analysis within dendrite at region B and C in Figure 2 (b) shows large percentage of Si and C which indicates these preplaced particles were existed in the sample of SiC coated DSS. This is the evident where the hardness values of the sample were increased. However, when the percentage of Si and C in DSS matrix was reduced as shown in Figure 3(c), the hardness values also reduced due to high dilution of melting during supplied high heat input of 1440 J/mm. This percentage of Si and C detected within dendrite at region D in Figure 2(c).

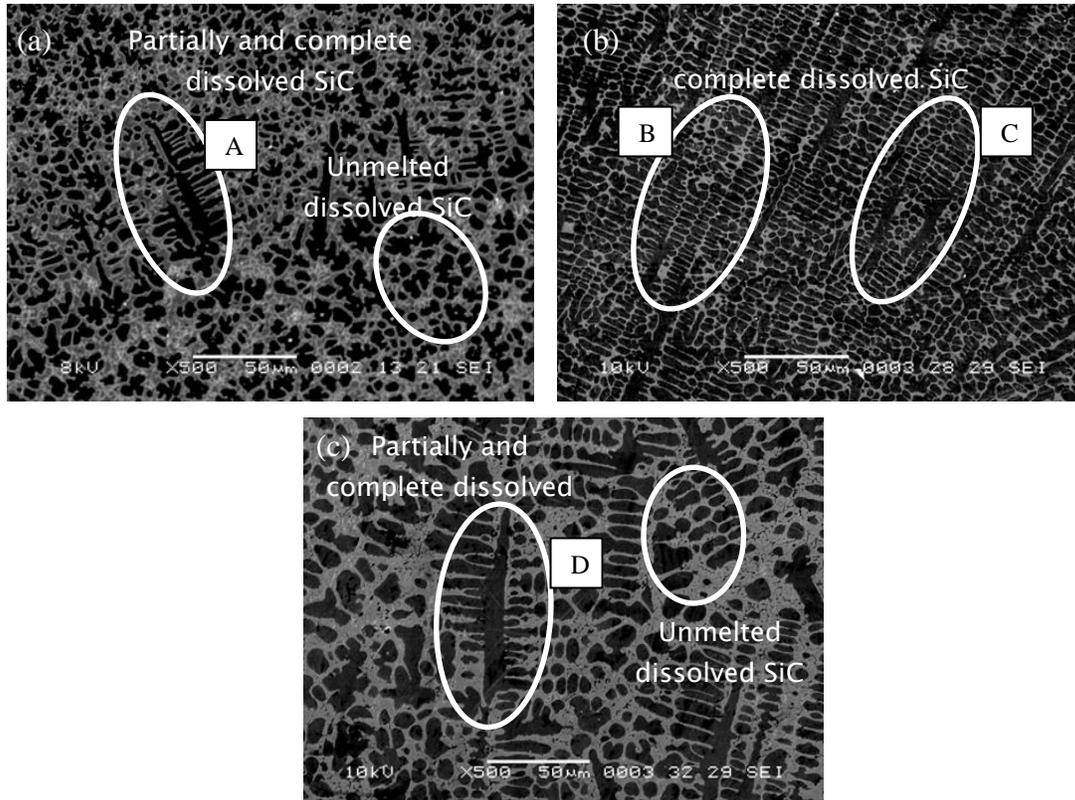


Figure 2: SEM micrographs for surface coated DSS at different heat input of (a) 480 J/mm (b) 768 J/mm and (c) 1440 J/mm.

3.2 Vickers micro-hardness profile of surface coated DSS

The hardness values plotted against the melt depth from surface with different heat input are shown in Figure 4. The measurement was taken from the middle surface coated DSS downwards into the depth of the melt pool. The hardness of modified surface layer achieved maximum hardness of 1000 Hv compared to only 250 Hv for substrate DSS. It is believed that dendrite formation contributes to the increment for the hardness values as discussed earlier in SEM results. The hardness profile shows a gradual decreasing trend from the top surface coated DSS to the bottom of the melt pool. It also confirmed by previous finding by Adeleke and Maleque (2015). This phenomenon can be attributed to the difference density of SiC (3.21 g/cm^3) and DSS (7.8 g/cm^3) tends to segregate SiC precipitates at the top of the melt pool where high-density iron precipitates at the bottom of the melt pool. Similar observation was found by Maleque et al. (2015).

The surface processed with heat input of 768 J/mm produced a maximum hardness of 1000 Hv which is 4 times higher than the substrate DSS. The higher hardness is contributed from high population of fine dendrite and thinly structure in the melt pool as can be seen in Figure 2(b). At heat input of 480 J/mm, the hardness values reduced to 710.9 Hv. This lower hardness might be due to lower population of dendrite compared to sample processed at 768 J/mm. The mixture of partial, unmelted and melted SiC particulates contributes this reduction of hardness values. Comparing these three different heat inputs, the lowest values of hardness achieved when

increased the heat input into 1440 J/mm. This is attributed to the mixture of partial and incomplete melting of the SiC particulates with DSS with low population of dendrite formation as shown in Figure 2(c). Similar justification by Lailatul and Maleque (2017) reported that reduction of hardness is mainly due to different structure of coarse dendrite formation and lesser population in the melt pool.

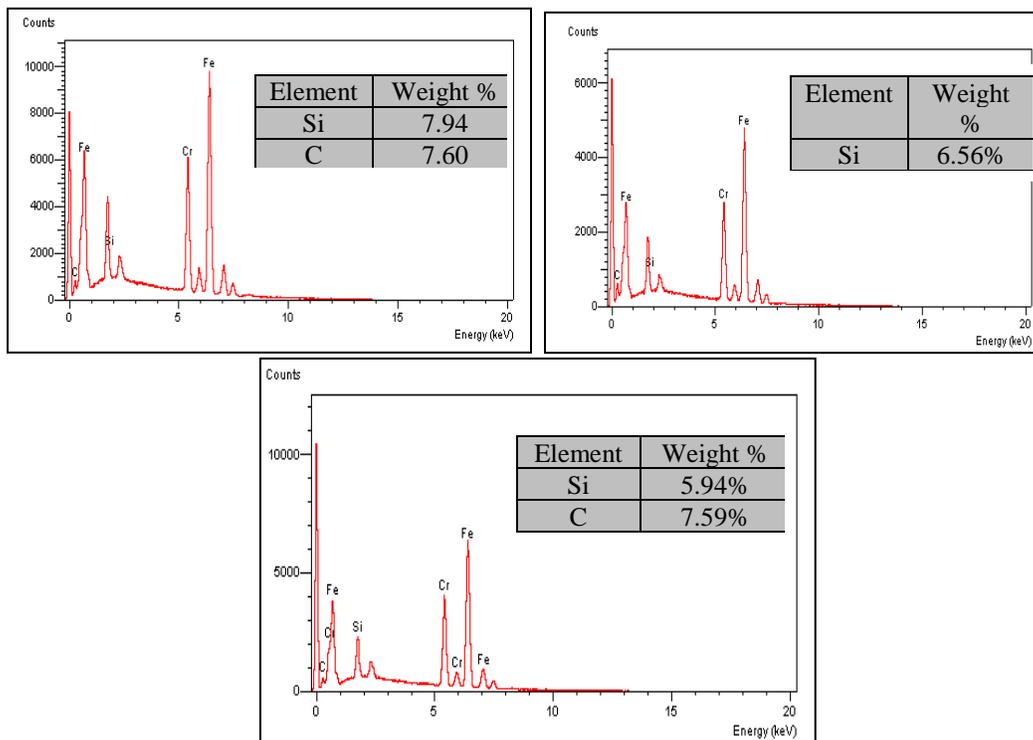


Figure 3: EDX analysis within dendrite correspond to (a) region A in Figure 2(a), (b) region B and C in Figure 2(b) and (c) region D in Figure 2(c).

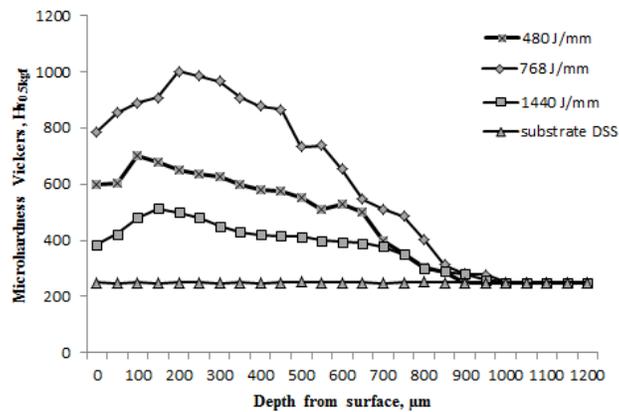


Figure 4: Micro-hardness depth profile of substrate and surface coated DSS at different heat input of 480 J/mm, 768 J/mm and 1440 J/mm.

3.3 Weight loss, wear depth and surface roughness of surface coated DSS

Figure 5 shows the weight loss of substrate DSS and SiC coated DSS at different heat input of 480 J/mm, 768 J/mm and 1440 J/mm. It can be seen that the surface coated DSS had a lower weight loss compared to substrate DSS. The sample processed at 768 J/mm showed the lowest weight loss with 0.41 mg. This is attributed to the formation of higher hardness obtained for this specimen due to high population of dendrite structure. The evidence for this justification is shown in Figures 2 and 4 which the formation of dendrite structure resulted high hardness of this surface coated DSS. However, for the specimen processed at 1440 J/mm, the weight loss is higher with 0.825 mg. This is directly related to lower hardness and lower population of dendrite formation. From this observation, it can be notified that the weight loss and hardness properties correlate well with the wear performance of the surface coated DSS.

Figure 6 shows the average surface roughness (Ra value) and depth of penetrations (Rz value) which measured by Mitutoyo Surface Test SJ-400 machine. The sample processed at different heat input showed smaller Ra and Rz indicating that the presence of SiC embedded in DSS surface matrix reduced the wear of the sample. Without presence of SiC in DSS matrix, average surface roughness was 3.31 μm compared to the presence of SiC coated DSS between 1.59 to 2.65 μm . For depth penetration, the value also reduced from 9.38 μm for substrate material into 6.57 μm until 8.62 μm for SiC coated DSS. Therefore, it can be reported that the higher the Ra and Rz values leading to higher wear weight loss of the material.

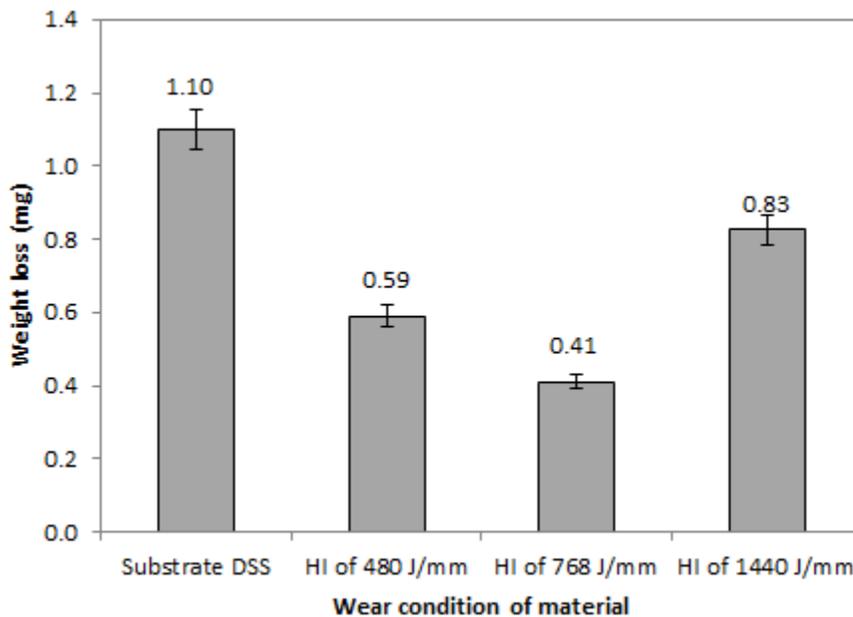


Figure 5: Weight loss for substrate DSS and surface coated DSS at different heat input of 480 J/mm, 768 J/mm and 1440 J/mm. Wear test conditions: frequency, 5 Hz; load, 30N; duration, 10 minutes; counter- part material, alumina ceramic ball.

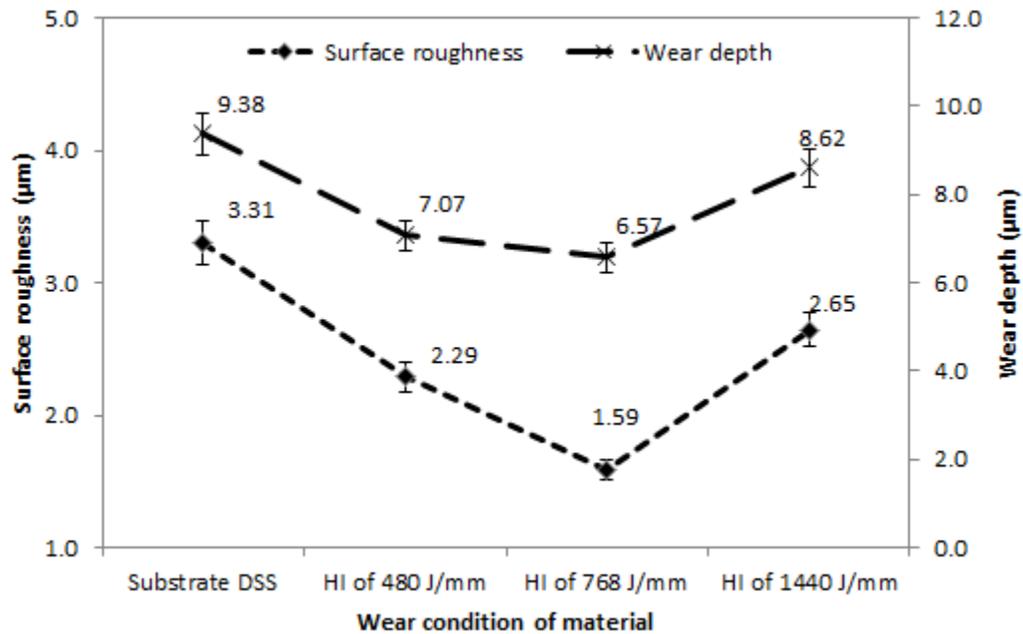


Figure 6: Surface roughness and wear depth of substrate DSS and surface coated DSS at different heat input of 480 J/mm, 768 J/mm and 1440 J/mm.

3.4 Coefficient of friction (CoF) of surface coated DSS

The average friction coefficient of substrate DSS and SiC coated DSS that processed under TIG cladding at different heat input has been shown and compared clearly in Figure 7. The friction coefficient for coated DSS varies from minimum 0.34 to maximum 0.58. During the tribo-tests, all SiC coated DSS showed lower CoF compared to substrate DSS with 0.73. The CoF for SiC coated DSS processed at heat input of 480 J/mm, 768 J/mm and 1440 J/mm are 0.41, 0.34 and 0.58 respectively. In view of the results obtained, the significant reduction in CoF can be contributed to higher volume of dendrite and hardness in the coating. The significant improvement of CoF was observed under heat input of 768 J/mm due to higher population of carbides and higher hardness, which cause the prevention of penetration of the load to the steel matrix. It can be seen that the CoF increase gradually at sample processed 480 J/mm and 1440 J/mm due to lower volume of dendrite and lower hardness obtained at this sample. This result coincide with the findings of Adeleke and Maleque (2015) which describes, the presence of TiC particle in titanium alloy has reduced the CoF of the material due to enhancement of hardness values.

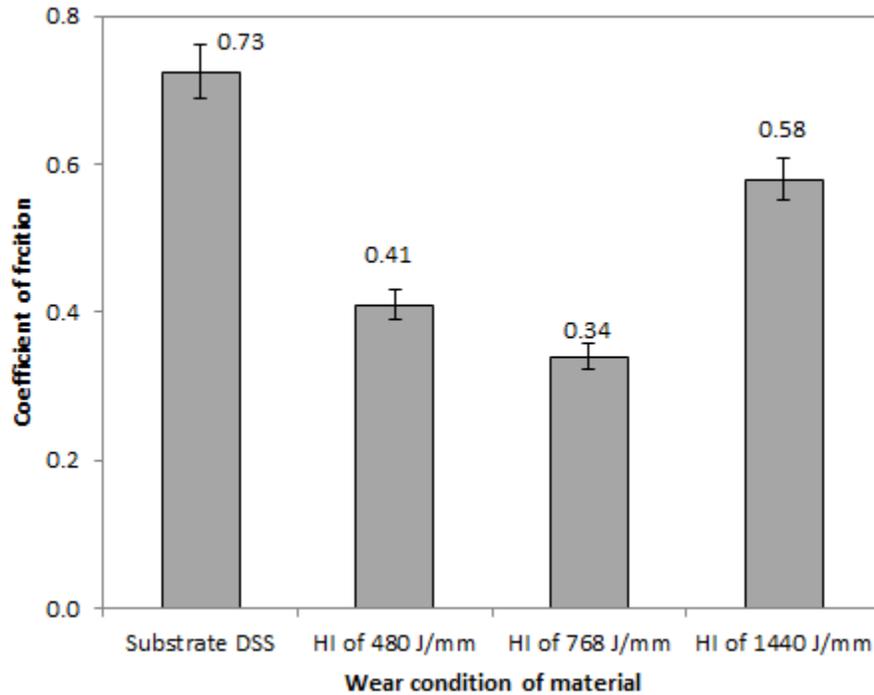


Figure 7: Friction coefficient of substrate and surface coated DSS at different energy heat input 480 J/mm, 768 J/mm and 1440 J/mm. Wear test conditions: frequency, 5 Hz; load, 30N; duration, 10 minutes; counter- part material, alumina ceramic ball.

3.5 Wear mechanism of surface coated DSS

Figure 8 shows the worn surface of the substrate DSS and SiC coated DSS at different heat input tested under dry sliding condition against the alumina ceramic ball. According to Figure 8(a), the worn surface of substrate DSS exhibited severe abrasion with ploughing and adhesive wear debris. However, the worn surface was improved for SiC coated DSS especially for sample processed at heat input of 480 J/mm and 768 J/mm as shown in Figure 8(b) and 8(c). Clearly, the sample produced mild wear surface and smooth abrasion mark with no indication of brittle deformation and coating detachment, suggesting strong bonding between SiC particles and DSS matrix interface. The SiC particles melted and embedded in DSS matrix formed intermetallic compounds which increase hardness and wear resistance of the material. As a result, the hard carbides formed on the DSS surface did not easily pull out from the surface during wear sliding. Similar observation found by Bello et al. (2016) on the low alloy steel preplaced with TiC particles. Figure 8(d) revealed that the worn surface was exhibited severe worn surface with ploughing when the surface processed at high heat input of 1440 J/mm. This phenomenon was due to lower hardness at this sample with low percentage of SiC ceramic particles.

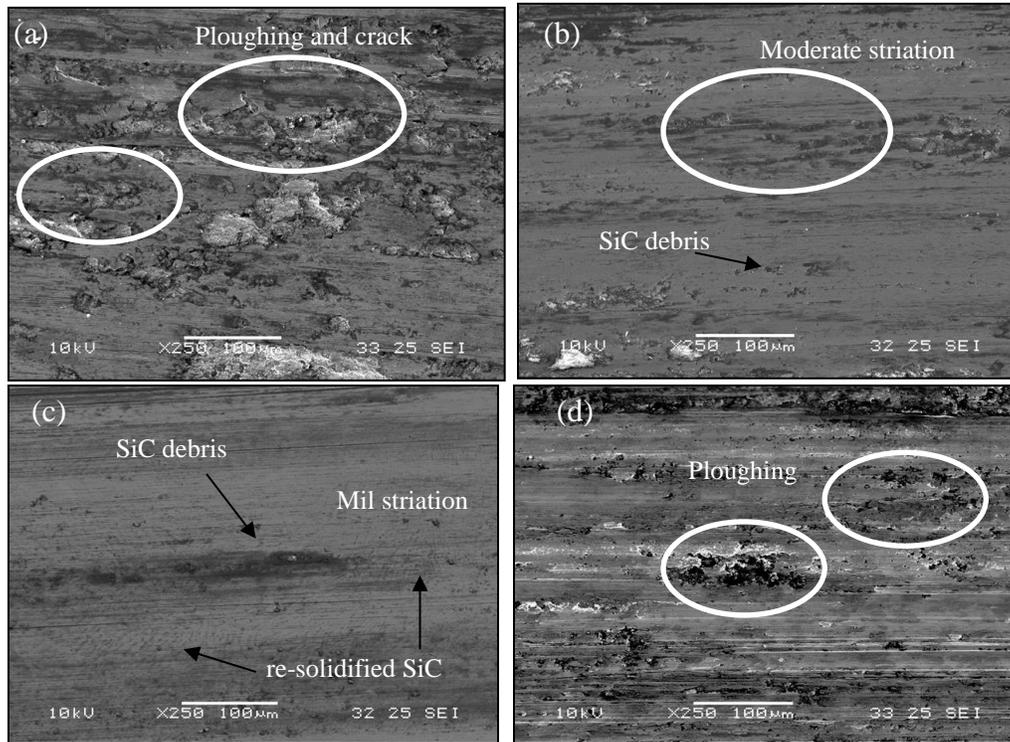


Figure 8: SEM micrographs showing worn surface (a) substrate DSS and surface coated DSS at heat input of (b) 480 J/mm (c) 768 J/mm (d) 1440 J/mm. Wear test conditions: frequency, 5 Hz; load, 30N; duration, 10 minutes; counter-part material, alumina ceramic ball.

CONCLUSION

In general, the presented results can be concluded as follows:

- (a) Surface coated DSS with SiC preplaced powder exhibited higher hardness which is almost 2 to 4 times higher compared to substrate material.
- (b) The wear behavior of coated DSS showed reduction of weight loss, surface roughness, wear depth and coefficient of friction due to the strong metallurgical bonding of SiC particles and DSS matrix which prevents the penetration of the abrasive alumina ceramic ball in to the DSS matrix.
- (c) The improvement of hardness and wear behavior attributed with the dendrite phases in the coated layer of DSS.
- (d) TIG torch heat input of 768 J/mm produced the best result on hardness and wear behavior in this investigation.
- (e) The worn surface of coated DSS showed very mild abrasive wear compared to substrate DSS with very severe wear with ploughing and crack marks.

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