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RESEARCH ARTICLE

MICROSTRUCTURAL CHARACTERIZATION AND WEAR PROPERTIES OF STEEL SURFACE COMPOSITE COATING WITH TiC NANOPARTICLES THROUGH GTAW ARCING TECHNIQUES

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Abstract. Gas tungsten arc welding (GTAW) for surface modification is a procedure that improves the substrate surface of material, effectively improving its hardness while influencing tribological behaviors. The aim of this work is to investigate the impact of the GTAW arcing method on the wear properties and microstructures of steel surface composite coatings containing nanoparticles of titanium carbide (TiC) ceramic particles. The GTAW process was conducted at different arcing currents which were 120 A, 140 A and 160 A with the same pulse frequency of 25 pulses per second (PPS). Microstructural characterization and wear testing were conducted using Field Emission Scanning Electron Microscopy (FESEM), and reciprocating tribometer, respectively. Findings indicate the arcing current significantly affects the microstructural regarding the composite coating with varying concentrations of the TiC nanoparticle's structure. The best result for Vickers microhardness value using current 140 A was found to be 367.21 Hv, while the lowest result of current using 120 A with 265.42 Hv. This is due to the high population of TiC nanoparticles in the composite coating. The lowest wear rate was observed for the current at 140 A with a value of 7.8 x 10^{-6} mm^3/Nm. These results demonstrate the increment of hardness resulting in the improvement of wear properties. The optimum arcing current of 140 A for GTAW arcing of type-2205 duplex stainless steel for surface modification can be recommended for wear industrial applications.

Keywords: Current, nanoparticles, composite coating, GTAW arcing.

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1. INTRODUCTION

Gas Tungsten Arc Welding (GTAW) is currently preferred over Metal Inert Gas (MIG) welding due to its ability to produce higher quality welds on thinner metals. Under optimal conditions, GTAW can achieve exceptionally high-quality welds. The mechanical characteristics of a welded joint are significantly affected by several GTAW input parameters, including the filler rod's size, the welding current, voltage, speed, and gas flow rate [1]. A broad range of materials, such as non-ferrous metals, aluminum, and stainless steel, can be welded using GTAW. It is frequently utilized in sectors such as construction, automotive, and aerospace industry. Its capacity to provide accurate, high-quality welds with little contamination is one of its main advantages. Additionally, the approach produces less spatter than conventional welding methods, which lessens the need for cleanup after welding. Moreover, GTAW may be used in a variety of positions, which increases its versatility in difficult environments [2].

Duplex stainless steel (DSS) is the most widely used of austenitic-ferritic steels exhibits a microstructure of austenite and ferrite. They are utilized in diverse applications because of their higher strength compared to austenitic steels and their suitability for corrosive environments [3]. Despite their high ductility, DSS are less formable than austenitic steels because of their greater strength. They are easy to weld and exhibit excellent resistance to stress corrosion cracking [4]. However, DSS exhibits certain weaknesses in hardness and wear resistance, which restricts its application in many tribological circumstances. Therefore, it is necessary to modify the surface of this material in order to address this issue. The GTAW arcing process with the deposition of ceramic particles presents a potential technique to enhance the hardness and reduce wear problem of this material [5].

The use of titanium carbide materials to create a hard surface layer is an appealing technology because it allows the surface to be tailored to match the requirements of diverse applications. This method is considered a new development in surface modification, as it includes spreading and depositing of titanium carbide particles into the metal surface. By using titanium carbide, the process of surface melting can provide a durable surface layer that improves the material's surface hardness and tribological performance [6]. In addition to the cladding materials system, the processing parameters significantly influence the microstructures and properties of the coatings.

Recent advancements in the use of nano-coatings as composite layers on stainless steel have gained notable interest. These coatings offer significant improvements in corrosion resistance and wear durability, providing advantageous volume and surface effects. Enhancing the wear resistance of material surfaces is essential, prompting research into high-performance nanomaterials for this purpose. Nanotechnology is extensively used in abrasive and corrosive environments found in modern machinery. Nano-composite materials and nano-structured coatings designed for wear resistance are utilized in turbine blades, combustion boilers, cutting tools and various other equipment [7]. Yin et al. [8] conducted a study using spray drying to blend FeAl powder with ZrO_2 nanoparticles and CeO_2 additives, creating innovative multi-component raw materials. These were then used to apply nanocomposite coating via plasma spraying on SUS321 stainless steel. The enhanced hardness, wear resistance, and fracture toughness of the nanocomposite coatings, compared to pure FeAl coatings, can likely be attributed to the reinforcing effect of the ZrO_2 nanoparticles.

In a study conducted by Chi et al. [9], the in-situ TiB_2-TiC reinforced Fe-Al composite coating was applied to Alloy 61S through laser material processing. This procedure resulted in an average micro-hardness increase to over seven times that of the original substrate material. In another research conducted by Paijan et al. [10], Taguchi's optimization method was used to analyze hardness characteristics and their effect on the microstructural properties of SiC-reinforced composite coatings on DSS. The SiC composite-coated DSS was produced using the GTAW surface modification technique, resulting in improved surface hardness at these specific process parameters: 80 A, 20 V, 1.0 mm/s transverse speed, and 25 L/min argon flow rate. The results show that applying a SiC ceramic coating on DSS significantly boosts hardness and wear properties.

Kumar et al. [11] conducted prior research on the surface modification of EN24 steel utilizing a multi-pass GTAW arcing technique. Research indicates that GTAW arcing surface modification improves the hardness and mechanical properties of EN24 steel. Other research conducted by Singh et al. [12] examined the development of wear-resistant WC-10Co-4Cr cladding on 18/8 stainless steel, via GTAW welding. The results of this study showed that partially melted WC grains contributed to increased hardness and wear resistance due to their increased resistance to wear. Numerous studies in the literature concentrate on the effect of wear properties with various composite coatings on surface modification using the GTAW method.

While several studies have investigated the effect of various ceramic reinforcements and GTAW process parameters on different steels, limited research has focused on the use of TiC nanoparticles in duplex stainless steels via GTAW surface modification. This study addresses this gap by examining the influence of arcing current on the microstructure, hardness, and wear resistance of TiC-reinforced composite coatings on DSS.

2. MATERIALS AND METHODS

The study focused on duplex stainless-steel grade 2205. Table 1 provides the chemical composition of the substrate [13]. The substrate was cut into dimensions of 50 mm x 35 mm x 10 mm which was then the substrate surface underwent abrasive grinding with SiC emery paper grade ranging from 240 to 2400. To eliminate impurities such as oil and grease, the surface was thoroughly rinsed with ethanol. For composite coating development, the TiC nanoparticles with particle size of 5 nm were pre-placed on the surface of the substrate. The nanoparticles were mixed with a small amount of ethanol, distilled water and polyvinyl acetate (PVA) to form a paste. The addition of the PVA is a function as binder to ensure that the TiC paste adhered to the substrate's surface during the flow of shielding gas of GTAW process. Lastly, the pre-placed samples underwent drying in an oven at 80 ºC for 1 hour to eliminate any remaining moisture from the TiC paste.

Table 1: Elemental chemical composition of grade 2205 duplex

Grade	C	Cr	Si	Mo	Mn	S	Fe
2205 duplex	0.026	22.06	0.69	2.58	1.74	0.008	Balance

The TiC nanoparticle was pre-placed on DSS and melted the substrate surface using GTAW arcing technique to develop the composite coating. A GTAW welding machine was used to develop the composite coating with arcing currents of 120 A, 140 A, and 160 A to investigate the impact of currents to the microstructural and wear properties of DSS. During the melting process, 15 L/min argon gas is used as a shielding gas to prevent excessive oxidation of the molten pool. The GTAW schematic diagram of welding procedure with 50% overlapping was performed to cover the whole surface of DSS to form a composite coating as shown in Figure 1. The overlapping melting technique is also important to ensure the entire surface is deposited and coated with TiC nanoparticles for surface modification [14]. Meanwhile, Figure 2 shows the DSS surface after developing a composite coating. The GTAW arcing parameters used in the composite coating development are displayed in Table 2.

Following the GTAW arcing process, the cross-section samples were cut using an EDM wire-cut. The cross-section samples were abraded with grinding and polishing equipment (Brand: Victor). Subsequently, the samples were polished with a velvet cloth using a 3 µm polycrystalline diamond suspension. The polished samples were then etched with Kalling's reagent using swab techniques for 5 seconds. The microstructure and elemental analysis were executed through field emission scanning electron microscopy (FESEM) and energy dispersive x-ray spectroscopy (EDX) analyzer. The EDX analysis was conducted to analyze the distribution of various elements. present in the composite coating layer. The Vickers microhardness testing machine was used to examine the hardness profile of the coating cross section samples with a force load 0.5 kgf and 10 s indentation time. To conduct a wear test, the grinding and polishing machine (Brand: Victor) was used to flatten and smoothen the surface of the sample's overlapping tracks. The sample's weight before and after test were carried out to examine the weight loss after test. A wear test was performed using a ball-on-disc reciprocating tribometer against an alumina ceramic ball, following the test conditions outlined in Table 3. The wear rate of the sample was determined utilizing the conventional formula and is presented in mm^3/Nm, as specified in equation 1 [15].

$$\text{Wear rate} = \frac{\text{Weight loss }(g) / \text{Density }(g/mm^3)}{\text{Normal load }(N) \times \text{Reciprocating distance }(m)} \tag{1}$$

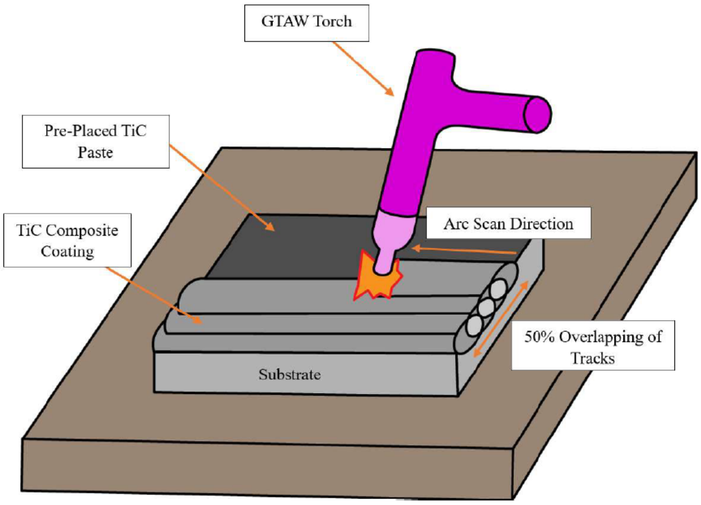


Figure 1: Schematic diagram of the GTAW arcing process and the track shifting scheme used to achieve a large area coating with 50% overlapping

Figure 2: The composite coating sample on DSS with 50% overlapping weldment

Table 2: GTAW arcing parameters used in the composite coating layer of DSS

Experiment no.	Argon gas flow rate (L/min)	Current (A)	Pulsed per second (PPS)
1		120	
2	15	140	25
3		160	

Table 3: The condition of the reciprocating wear test

Specimen	Reciprocating wear test conditions for linear motion
Applied load	20 N
Frequency	15 Hz
Wear test duration	15 minutes
Counter-part body	6 mm diameter Alumina ceramic ball

3. RESULTS AND DISCUSSION

3.1 Micro-hardness Profile Analysis

Measurements of microhardness from cross-sectional samples were carried out at various points along the surface composite coating DSS with the deposition of TiC nanoparticles. The microhardness profiles from different regions were plotted relative to the distance from the upper surface into the substrate material, as illustrated in Figure 3. According to the hardness profile result, a significant difference is observed in the hardness value due to deposition of TiC nanoparticles in the composite coating layer DSS. The fluctuation in hardness values is believed to be due to the inhomogeneous distribution of TiC nanoparticles in the composite coating layer. This can be clearly observed in Section 3.2 (morphology results).

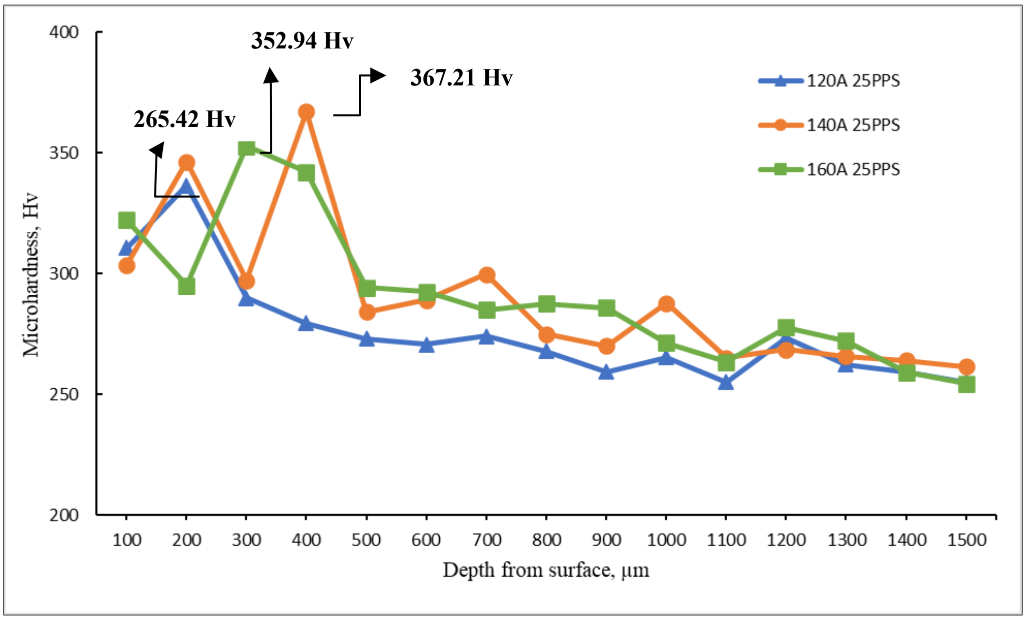


Figure 3: Microhardness profile with varying arcing currents

From Figure 3, the GTAW arcing current of 120 A exhibited the lowest hardness of 265.42 Hv. At this lower arcing current, insufficient energy likely resulted in poor distribution and lower incorporation of TiC nanoparticles, leading to a reduced hardness. The observation of the plot shows that the value of 367.21 Hv was the highest hardness in the composite coating layer with an arcing current of 140 A. This increase in hardness can be attributed to the higher concentration and better distribution of TiC nanoparticles, which effectively strengthen the composite coating. However, the hardness reduced at a higher current of 160 A due to a lower concentration of TiC nanoparticles as can be seen in Figure 4 (morphology result). These results align with the study by Debta et al. [16], which demonstrated that adding nano-Y_2O_3 enhanced hardness values, increased the efficacy of precursor melting, and completely melted the TiC particles, transforming them into spread dendritic structure during solidification. This also enhances wear resistance, with the coefficient of friction (CoF) indicating nearly four times less wear for the TiC-Co-2%Y_2O_3 coating compared to the TiC-Co coating. The incorporation of nano-Y_2O_3 resulted in significant refinement of the grain structure of the clad material, which also led to an increase in the coating's ductility and fracture toughness.

3.2 Morphology and Elemental Analysis

Figure 4(a) to (c) illustrates the cross-section morphology of the composite coating DSS at different arcing currents. The findings suggest that arcing current notably influences the morphology of the composite coating, with TiC nanoparticles present in the composite coating layer. It was observed that the TiC content in the composite coating layer increased with higher arcing currents. Dark irregular shapes were observed in all coatings, with their quantity increasing progressively from 120 A to 140 A, as shown in Figure 4(b) and 4(c). The dark particles showed were residual TiC nanoparticles, which indicated that the TiC powders had not completely melted, and their concentration had gradually dispersed from low population to high population at higher current. The white region is observed as matrix region of DSS in the composite coating layer. However, at a higher current of 160 A, a reduction in TiC content within the coating layer was observed. Excessive heat input likely caused vigorous melting and fluid flow, reducing the retention and embedding of TiC nanoparticles in the coating, as seen in Figure 4(c). The evidence of the presence of TiC nanoparticles was revealed in EDX spectra as presented in Figure 5.

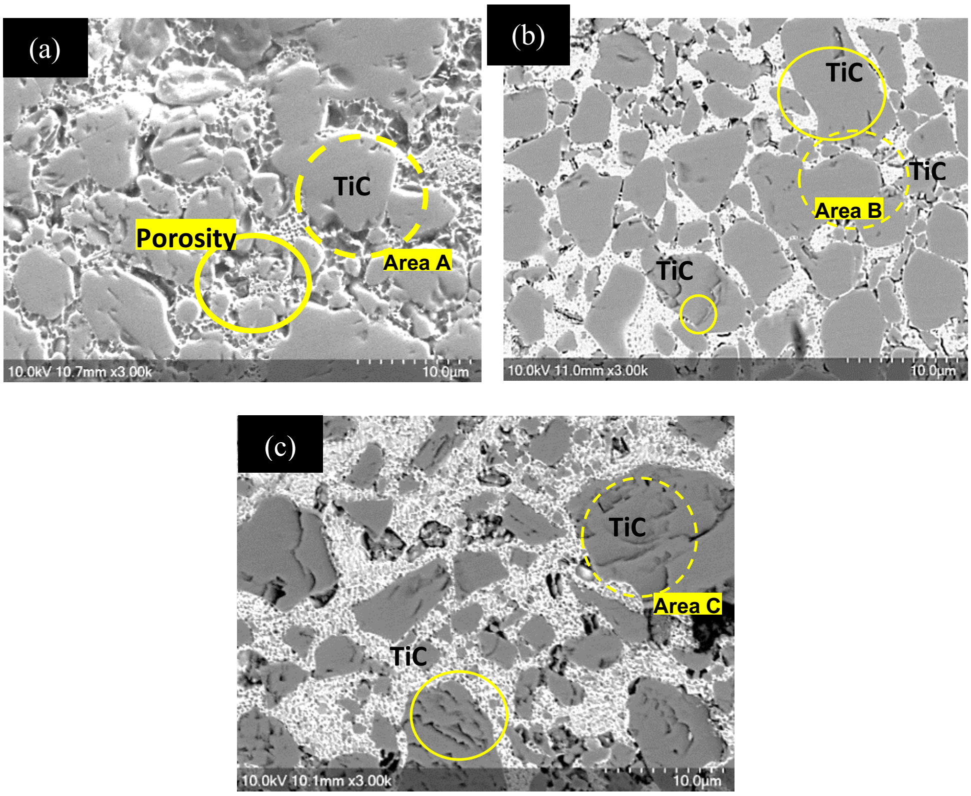
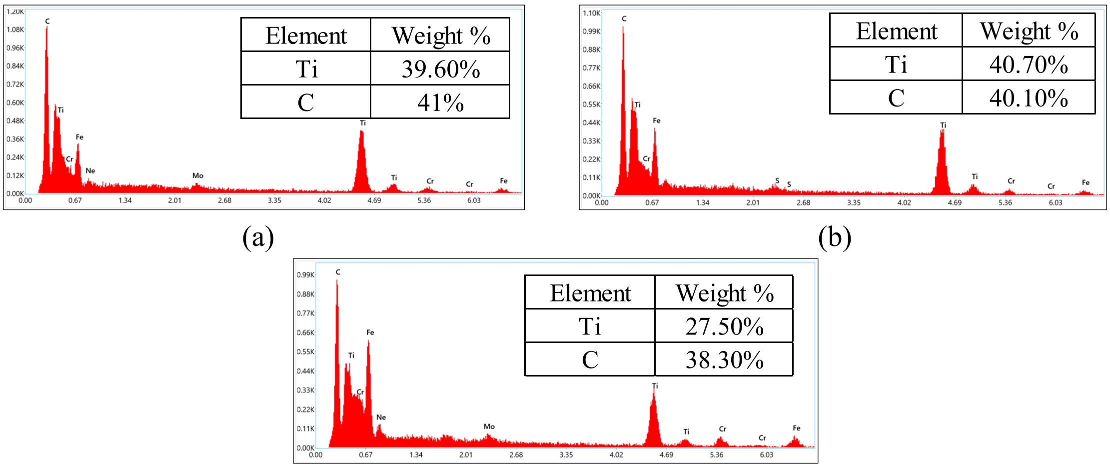


Figure 4: FESEM micrographs of cross-sectional images with dark appearance (TiC nanoparticles region) and white appearance (matrix region) at different arcing currents of (a) 120 A, (b) 140 A and (c) 160 A

Figure 4(a) shows the population of TiC nanoparticles observed in the sample and supported by EDX result (Figure 5a) with the percentage of the Ti and C with 39.6% and 41%, respectively. It can be observed the spherical shape of TiC is large and dispersed in the sample. The porosity also been observed in this sample might be due to improper settings for current of 120 A can affect the stability of the arc and lead to porosity. With the increment of arcing current 140 A, it can be observed the spherical shape with dark appearance of TiC nanoparticles became smaller with better dispersion and compact in the composite coating layer as shown in Figure 4(b). It can be seen also that the highest concentration of TiC nanoparticles was observed in this sample with composition of Ti (40.7%) and C (40.1%) from EDX result as shown in Figure 5(b). The reason behind of this might be due to appropriate processing energy to disperse well of TiC nanoparticles in the sample. However, the population of TiC in the composite coating reduced at higher current of 160 A as shown in Figure 4(c). The EDX spectra results reveals the reduction of Ti and C composition with 27.5% and 38.3%, respectively as depicted in Figure 5(c). This is attributed to vigorous stirring leading to strong dispersion and less distribution of TiC in the composite coating layer. The findings were consistent with previous research by Gupta et al. [17], which indicated that various shaded regions, black and grey in colour, were observed when TiC-TiB_2 was used as a reinforcement on BS 304S31 produced through the GTAW arcing process.



(a) (b) (c)

Figure 5: EDX spectra for TiC composite coating at different arcing currents (a) 120 A (area A), (b) 140 A (area B) and (c) 160 A (area C)

3.3 Tribological Properties on Wear Rate and Worn Surface Mechanism

The composite coating layer was subjected to a dry ball on disc test at loads of 20 N and a frequency of 15 Hz. The wear rate and worn surface at different arcing current were presented in Figures 6 and 7, respectively. The increased concentration of TiC nanoparticles at a GTAW arcing current of 140 A resulted in the lowest observed wear rate for this sample with a value of 7.8 x 10^{-6} mm^3/Nm. Meanwhile, the wear rate value for 120 A and 160 A produced almost similar result with value of 9.3 x 10^{-6} mm^3/Nm and 8.5 x 10^{-6} mm^3/Nm, respectively. The increasing value of the result was due to less concentration of TiC nanoparticles composite coating layer for both samples. From this finding, it can be concluded that using TiC nanoparticles resulting the improved wear properties of the composite coating layer. Previous researcher Kumar et al. [18] found out that the TiB_2 coating with Co addition with lower current has improved the microhardness and reduced the wear rate compared to the coating without Co. The findings suggest that TiB_2 ceramic coatings with Co addition enhance hardness and durability, making them suitable for wear-resistant applications.

In order to examine the wear mechanism, the surface morphology of the worn area was analysed, as depicted in Figure 7. The deposition of TiC nanoparticles at a GTAW arcing current of 120 A resulted in relatively low matrix hardness, leading to reduced shear resistance and ploughing resistance, thereby promoting more severe wear between the composite coating layer and the alumina ceramic ball. The surface of the abrasion marks exhibited distinct adhesion marks and significant scratches. As the current arcing increased to 140 A, the grooves on the wear surface reduced progressively, resulting in a significant reduction in the depth of the wear marks, which became predominantly shallow, as illustrated in Figure 7(b). The incorporation of TiC nanoparticles into the composite coating matrix significantly reduced the wear rate and enhanced wear resistance. The wear mechanisms of the composite coating surface are characterized by abrasive wear and micro-cutting.

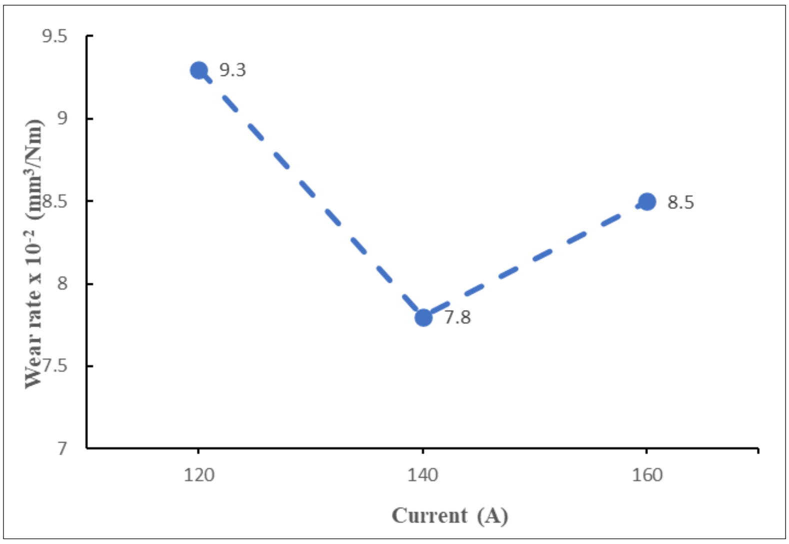


Figure 6: Wear rate and at different arcing currents of (a) 120 A, (b) 140 A and (c) 160 A

Figure 7(c) indicates a significant wear mark accompanied by the development of a spalling crater. The high-speed wear process of the composite coating layer results in a rapid rise in the temperature of the wear surface, causing O_2 in the air to readily react with iron (Fe) to form an oxide film, which reduces the friction of the layer and consequently reduces material wear. This behaviour is attributed to the reduced TiC particle concentration, which limits reinforcement of the matrix, combined with severe plastic deformation under contact stress. The wear mechanism reveals that ploughing and adhesive wear are the predominant processes in this sample. These results are in line with an earlier study, which demonstrated that incorporating SiC ceramic particles on DSS decreased the wear rate to below 50% of that of the DSS substrate, due to a thermal input of 0.768 kJ/mm [19].

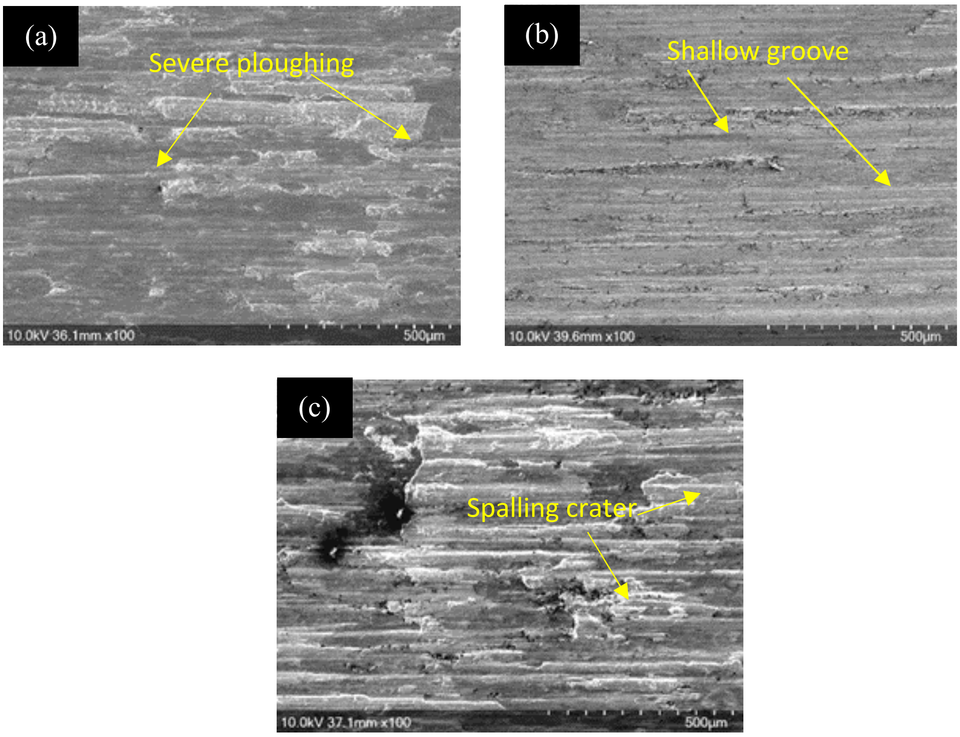


Figure 7: SEM image of the wear ball on disc at different arcing currents (a) 120 A, (b) 140 A and (c) 160 A

4. CONCLUSIONS

This research was carried out to study the effect of current on the microstructural characterization and wear properties of composite coating layer with TiC nanoparticles through GTAW arcing. The study was performed successfully with steel surface AISI Duplex-2205 which has been effectively achieved by the deposition of 5 nm TiC nanoparticles and melting using the GTAW arcing process. From this work, it was found that the highest hardness of the composite coating layer was obtained using a current of 140 A of the GTAW process with a high population of TiC nanoparticles. The microstructural examination reveals the deposition of ceramic particles in the DSS materials have produced the irregular shape of TiC nanoparticles in the composite coating layer. Meanwhile, the ideal arcing current of 140 A resulted in the minimal wear rate of 7.8 x 10^{-6} mm^3/Nm with abrasive wear and shallow groove mechanism.

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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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