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RESEARCH ARTICLE

EFFECT OF PULSE FREQUENCY ON MICROSTRUCTURE AND TRIBOLOGICAL PROPERTIES OF TiC NANOCOMPOSITE COATINGS ON ASTM A240 STAINLESS STEEL VIA TIG TORCH MELTING

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Abstract. ASTM A240 duplex stainless steels offer improved mechanical properties and better corrosion performance, making them widely used in industries such as oil and gas, chemical processing, marine, and structural applications. Despite its high strength and corrosion resistance, the industrial application of the substrate is limited by low surface hardness and wear resistance. To overcome these issues, TiC nanoparticles were melted using TIG torch method at a constant current of 140 A and three different pulse frequencies (15, 20, and 25 PPS) to produce TiC nanocomposite coatings. Therefore, this study investigates the influence of pulse frequency on the surface reinforcement of ASTM A240 grade S31803 using TiC nanoparticles deposition via the Tungsten Inert Gas (TIG) torch method. The microstructural features, coating thickness, and phase structure were investigated via digital microscope, Field Emission Scanning Electron Microscopy (FESEM) and X-ray Diffraction (XRD) analysis, while the mechanical properties were determined using Micro-Vickers hardness and linear reciprocating wear testing techniques. As observed, an increase in pulse frequency considerably improves microstructures and tribological properties. Among all the samples, a pulse frequency of 25 PPS showed superior behaviour with a coating thickness of 1.78 mm and maximum microhardness of 415.96 HV due to formation of CrTi and CrC intermetallic phases. Additionally, lowest coefficient of friction (CoF) of 0.08 was attained with minimal surface ploughing for TiC nanocomposite coating.

Keywords: Pulse frequency, nanocomposite coating, intermetallic compound, TIG, surface modification.

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1. INTRODUCTION

The Tungsten Inert Gas (TIG) welding process is a precise and controlled technique commonly used in high-accuracy industries, including aerospace, automotive, and medical device production [1, 2]. The process utilizes a non-consumable tungsten electrode and an inert gas shield (typically argon) to protect the weld pool [3]. Known for producing high-quality welds with few defects, TIG welding demands careful adjustment of several parameters, with pulse frequency being particularly significant [4]. Pulse frequency, expressed in pulses per second (PPS), determines how often the welding current switches between high and low levels [5]. This parameter directly influences arc stability, penetration depth, and thermal input, making it crucial for precision welding.

ASTM A240 with grade S31803 duplex stainless steel (DSS) is highly valued in industrial applications due to its outstanding corrosion resistance, high mechanical strength, and thermal stability, making it ideal for environments requiring robust surface performance [6,7]. When subjected to surface modification techniques like welding, cladding or heat treatment, this material exhibits enhanced durability and wear resistance, even under extreme operational conditions [8]. In parallel, TiC-reinforced composite coatings have emerged as a promising solution for surface enhancement, owing to their exceptional mechanical and tribological characteristics [9]. The addition of TiC powder facilitates microstructural refinement and dispersion strengthening, significantly improving hardness and wear resistance [10]. As a result, applying TiC-based composite coatings to the substrates presents a viable strategy for enhancing performance in high-stress applications involving severe wear and elevated temperatures.

During the melting process of TIG torch for surface modification, the interdiffusion of atoms from the substrate and the coating material occurs. This chemical reaction between the substrate and alloying elements forms intermetallic compounds [11]. When incorporated into composite coatings, intermetallic significantly improves coating performance by increasing load-bearing capability and minimizing wear rates [12]. Such enhancements make these compounds indispensable for demanding sectors including aerospace propulsion systems, high-performance automotive components, and power generation equipment, where surface reliability directly impacts service life and operational effectiveness [13].

Recent research has demonstrated substantial progress in surface engineering approaches. In a notable study, Maleque et al. [14] demonstrates that TIG torch surface melting is a cost-effective method to enhance the tribological properties of titanium alloy grade 5 (Ti6Al-4V) by preplacing the substrate with silicon carbide (SiC) powder size 20 μm and melting it. Optimized process parameters included current of 120 A, 18 voltage and travel speed 1.2 mm/s determined through the Taguchi method. Results showed significant improvements, including maximum surface hardness of 482.3 HV, a reduced wear rate of 0.1711 mm^3/Nm, and a lower CoF of 0.39. Voltage and SiC powder size were identified as key factors influencing these enhancements, underscoring the method’s viability for applications requiring superior durability and wear resistance.

Previous studies have demonstrated that surface modifications achieved via TIG torch melting with ceramic powder enhance the surface properties of various substrate materials, particularly in terms of hardness and wear resistance. However, prior research has largely centered on the influence of other process parameters or ceramic particles while overlooking the specific impacts of pulse frequency during the incorporation of composite coating into the hard facing of substrate material. While previous studies have utilized TIG torch processing for surface hardening, the relationship between pulse frequency and the effect of TiC nanoparticles distribution on DSS surfaces remains poorly understood. In particular, it is still unclear how the TiC nanoparticles can be deposited onto the substrate by altering the pulse frequency from 15 to 25 PPS. The pulse frequency plays a pivotal role in determining the microstructural evolution, deposition, intermetallic phase formation and wear properties within the nanocomposite coating layer. By examining these factors, this research is to explain the direct correlation between pulse frequency and the resultant coating properties, such as surface hardness and wear resistance. Furthermore, understanding the impact of this crucial process parameter is anticipated to significantly advance the development of TiC nanocomposite coatings tailored for superior tribological performance.

2. MATERIALS AND METHODS

2.1 Raw materials and nanocomposite coating preparation

In this work, ASTM A240 stainless steel with dimensions of 50 mm × 35 mm × 10 mm was used as the substrate for surface modification by depositing a TiC nanoparticle into substrate surface. The chemical compositions of substrate material (ASTM A240) are displayed in Table 1 [15]. To achieve a smooth surface, the substrate was subjected to abrasive grinding using coarse-grit paper ranging from 60 to 240. It was then thoroughly cleaned with ethanol and distilled water to remove contaminants such as oil and grease. Subsequently, the nanoparticles with a size of 5 nm were mixed with ethanol, distilled water, and polyvinyl acetate (PVA) to form a paste. The PVA acted as a binder to ensure the nanoparticles paste adhered to the substrate during the TIG torch process, even under the flow of shielding gas. The paste was then evenly spread over the substrate's surface and subsequently heated in an oven at a constant temperature of 80 °C for 1 hour.

Table 1: Elemental chemical composition of ASTM A240 [15]

Type	C	Cr	Si	Mo	Mn	S	Fe
ASTM A240	0.03 %	18 %	0.75 %	3 %	2 %	0.03 %	Balance

2.2 Development of TiC nanoparticles and surface characterization

The nanocomposite coatings were deposited via the TIG torch method using a constant current of 140 A and pulse frequencies of 15, 20, and 25 PPS. The detailed conditions for the parameters used for this process are displayed in Table 2. During the TIG torch process, 15 L/min of argon gas is used as shielding gas to prevent air from entering the molten pool. This work aims to investigate the influence of these parameters on the microstructural and wear properties of ASTM A240. Initially, the welding procedure with 50 % overlapping was performed to cover the whole surface of substrate to form a nanocomposite coating. The overlapping melting technique is also important to ensure complete and uniform deposition of TiC nanoparticles across the surface.

Table 2: Process parameters utilized for the deposition of TiC nanocomposite coatings via the TIG torch method

Exp. run	TiC powder size (nm)	Current (A)	Pulse Frequency (PPS)
1	5	140	15
2			20
3			25

After the completion of the TIG torch procedure, the coated substrate was cleaned to remove any excess bonded powders and subsequently cut into cross-sections using an EDM wire-cutting process. The cross-section sample was subsequently ground and polished with abrasive grit sizes of 60, 240, 300, 400, 600, 800, and 1200 followed by velvet cloth polishing using an alumina suspension until the substrate mirror finish. Thereafter, the samples were etched with Kalling's reagent to expose the microstructure of the nanocomposite coating as shown in Figure 1. The thickness layer of nanocomposite coating was measured using digital microscope under 200x magnification. The micrograph analysis of the cross-sectional sample was conducted using FESEM at 3000x magnification.

Furthermore, XRD examination was conducted on the surface of the substrate to analyse the intermetallic compound. The resulting diffraction patterns were then processed and visualized using OriginPro software.

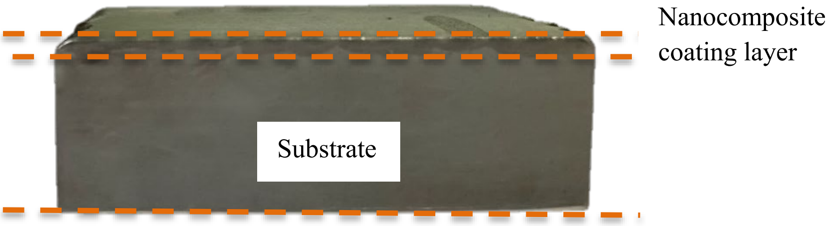

Figure 1: Cross section of the ASTM A240 after etching

2.3 Micro Vickers hardness

The micro-Vickers hardness values were measured with a diamond indenter, with a force load of 0.5 kgf and a 10-second indentation time. The hardness measurements were plotted along the distance from the top surface into the base substrate material. The highest value was recorded as a result of the indentation result across the depth profile in the deposition of nanocomposite coating. The test results were measured based on the average of twenty indentations from each sample.

2.4 Tribological properties

For the reciprocating wear test, the overlapping track underwent abrasive grinding to achieve flattened and smooth surface. A wear test was performed using a ball-on-disc linear reciprocating tribometer against an alumina ceramic ball, as shown in Figure 2. The tests were performed under a normal load of 20 N at a reciprocating frequency of 5 Hz with a stroke length of 15 mm for a total sliding duration of 15 minutes. The sample's weight before and after the test was carried out to examine the weight loss. Subsequently, the resulting worn surfaces were subjected to analysis using FESEM equipment.

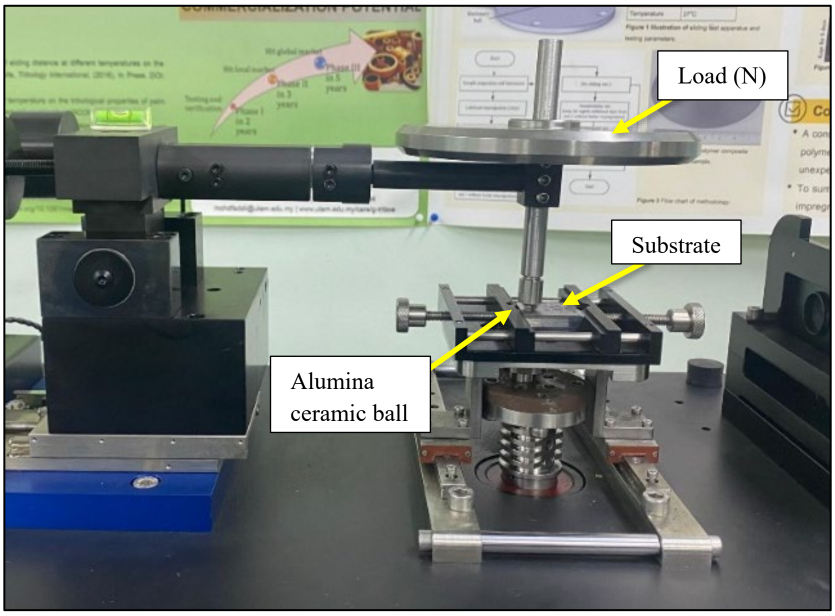

Figure 2: Linear reciprocating wear test equipment

3. RESULTS AND DISCUSSION

3.1 Effect of pulse frequency on the structural characteristic

The incorporation of TiC nanocomposite coatings on the substrate via TIG torch method demonstrates that pulse frequency significantly influences nanocomposite coating characteristics. Cross-sectional analysis in Figures 3(a-c) demonstrates the enhancement of coating thickness layer with increasing pulse frequency. To ensure statistical reliability, three measurements were taken at different locations for each sample, and the average values were utilized. These findings are quantitatively supported by the bar chart in Figure 4, which incorporates error bars to represent the standard deviation of the thickness readings. At a lower pulse frequency of 15 PPS (Figure 4(a)), the nanocomposite coating attains a thickness average of 1.41 mm, which is significantly thinner than coatings produced at higher frequencies. This diminished TiC nanoparticles deposition is attributed to insufficient heat accumulation during lower pulsed deposition process. The lower pulsing rate leads to shorter durations of peak energy input, which limits the effective incorporation of nanoparticles onto the surface's substrate. Furthermore, the microstructural analysis indicates significant agglomeration of TiC nanoparticles in the nanocomposite coating matrix. This phenomenon results from insufficient thermal energy for uniform dispersion during deposition.

Moreover, increasing the pulse frequency to 20 PPS results in a thicker and more uniform coating layer measuring at average of 1.50 mm, demonstrating improved deposition efficiency compared to lower frequencies. This enhancement is attributed to greater heat accumulation, which facilitates deeper material fusion and more consistent incorporation of TiC nanoparticles onto the surface's substrate. Microstructural analysis corroborates these improvements, revealing a well-dispersed distribution of TiC nanoparticles with minimal agglomeration. The increased pulse frequency enhances the mobility of the TiC nanoparticles, as evidenced by the distribution patterns observed in the cross-sectional micrographs in Figures 3(a) and 3(b).

At the highest frequency of 25 PPS, the coating thickness reaches at average of 1.53 mm, the maximum layer observed in this study. The rapid pulsing action generates repeated cycles of the deposition of TiC nanoparticles onto the substrate. The pulse frequency of 25 PPS produced the best parameter setting for achieving a distribution of TiC nanoparticle concentration. Unlike lower frequencies, the rapid pulsing at 25 PPS maintains a stable melt pool, which allows the TiC nanoparticles to be distributed more homogeneously. This is supported by the FESEM observations in Figure 3(c), which show the highest population of TiC nanoparticles. The increase in pulse frequency ensures that the nanoparticles are effectively trapped within the refined grain structure, resulting in the superior hardness and wear resistance observed. Similarly to the trend by Zhang et al. [16] investigated the effects of pulse frequency (PF) and duty cycle (DC) on the properties of Ni-W/TiN nanocomposite coatings. It was found that increasing the PF from 50 Hz to 150 Hz led to an increase in TiN content from 6.4 wt.% to 9.6 wt.%, resulting in a denser and more uniform coating structure. The coating thickness achieved at a PF of 150 Hz and DC of 10 % was approximately 39.8 µm.

XRD analysis was conducted to identify the phases present in the nanocomposite coatings. As depicted in Figure 5, the varying pulse frequency of TIG torch process influenced the phase compositions. The primary phases observed in the nanocomposite coatings were γ-Fe and α-Fe, which is a typical phase observed in substrate material. A comparison between the XRD patterns of the substrate and the nanocomposite coating reveals the emergence of new peaks, indicating the formation of intermetallic compounds following the deposition of TiC nanoparticles. Additionally, secondary phases such as CrTi, CrC, and TiC were detected, which became more prominent with increasing of TiC deposition, indicating a clear relationship between TiC concentration and phases composition. This also indicates the formation of intermetallic compound in the nanocomposite coating leads to high hardness and wear resistance.

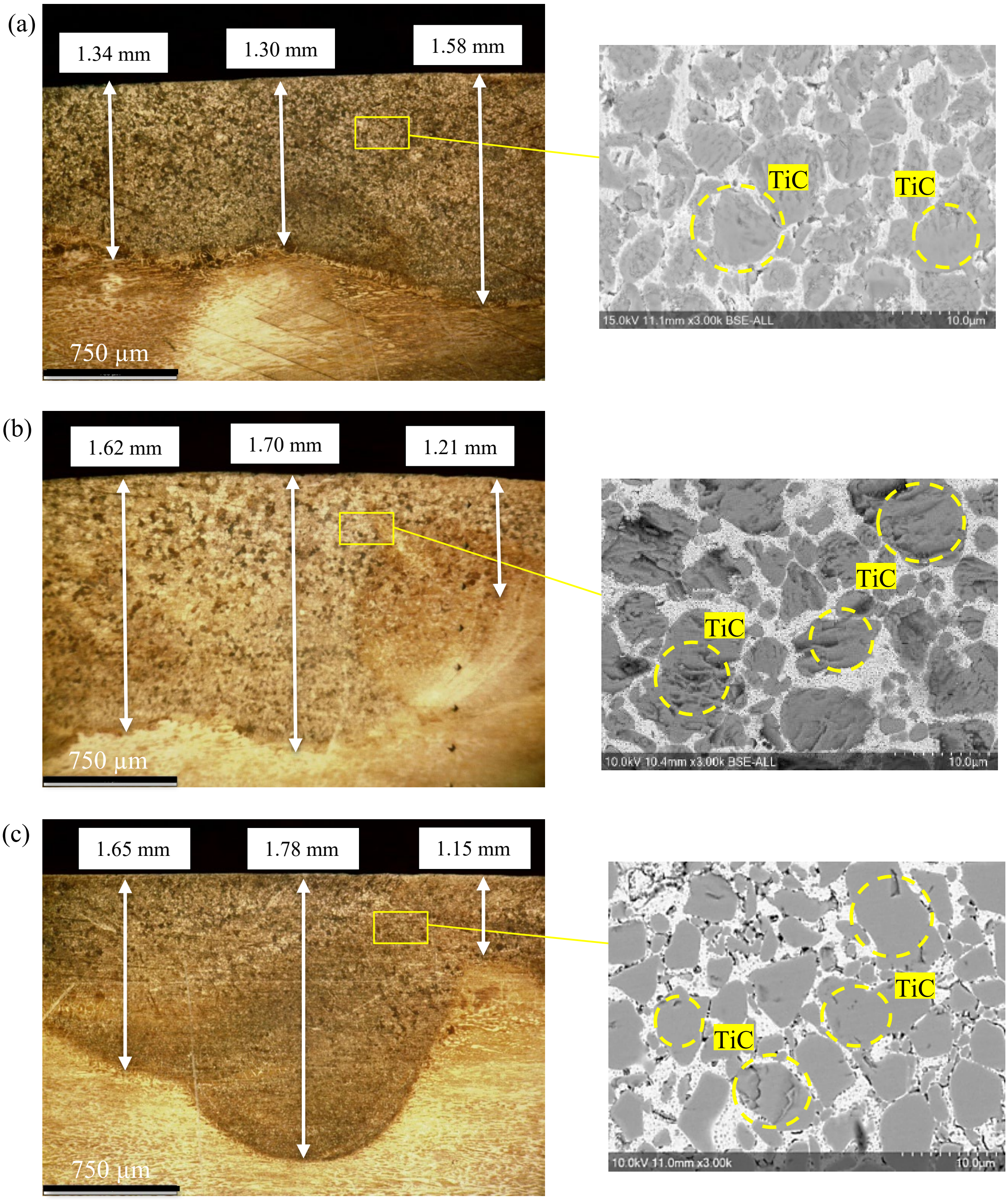

Figure 3: Thickness layer (digital microscope) and FESEM micrographs of cross-sectional images for TiC nanocomposite coating at different pulse frequency settings (a) 15 PPS, (b) 20 PPS and (c) 25 PPS

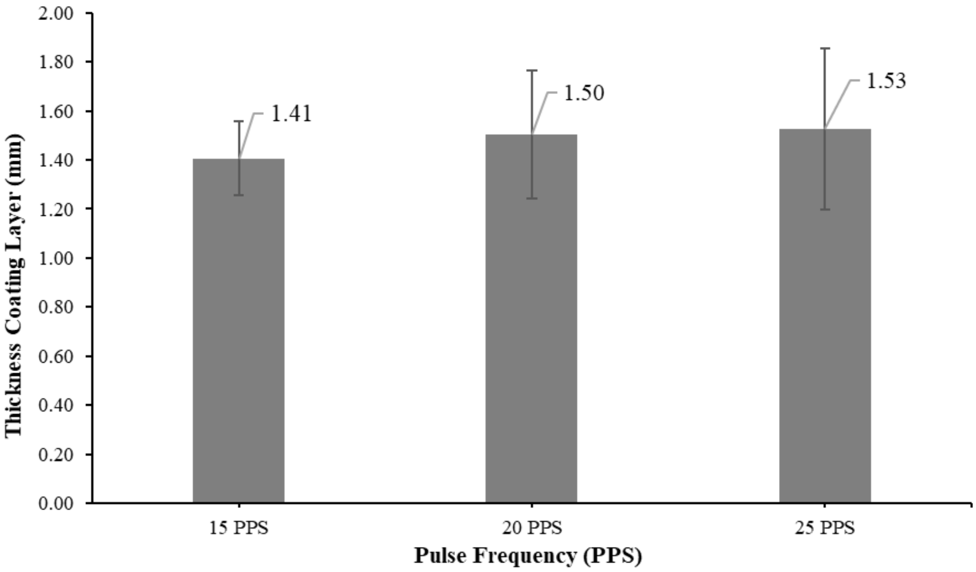

Figure 4: Average coating thickness of the TiC nanocomposite layer at different pulse frequencies. The error bars represent the standard deviation calculated from three separate measurements for each sample

It can be seen also in Figure 5, the slight variations of the peak intensities whereby the higher pulse producing higher peak compared to lower pulse frequencies. The observed phase variations can be linked to the nanocomposite coating thickness layer and microstructure. By increasing the pulse frequency, the TiC nanoparticles content not only alters the phase composition but may also influence the coating's morphology and uniformity. This interplay between phase formation, thickness, and microstructure underscores the role of TiC nanoparticles and intermetallic compound in tailoring the nanocomposite coating's properties.

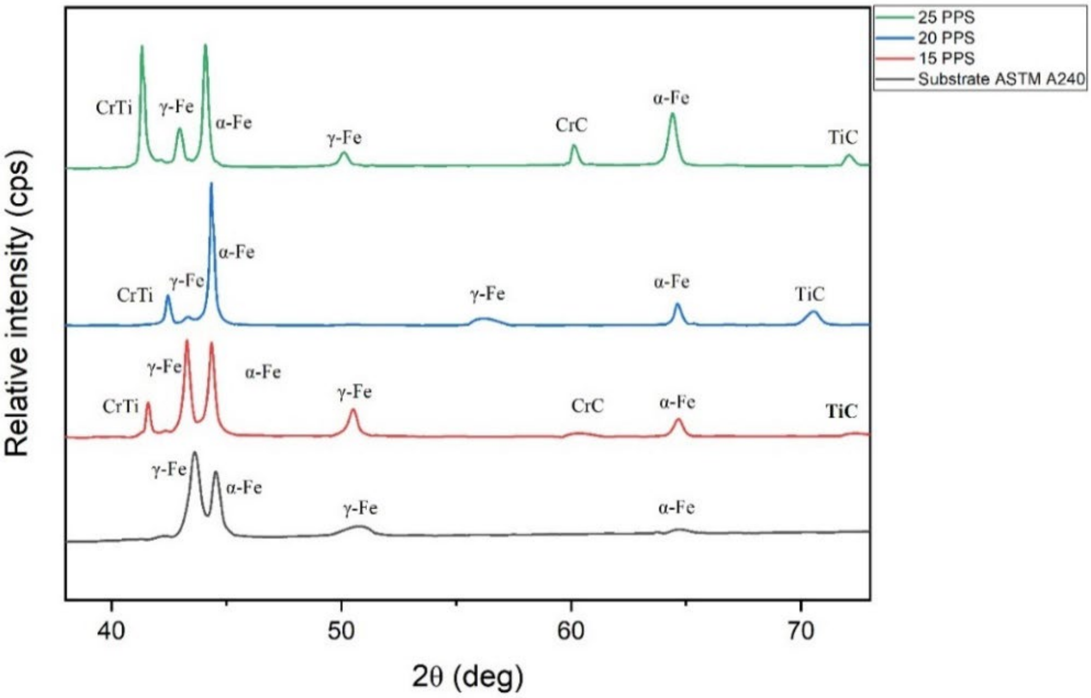

Figure 5: XRD result obtained from the nanocomposite coating that was produced using a TIG pulse frequency at 15 PPS, 20 PPS and 25 PPS

The XRD patterns in Figure 5 confirmed the formation of CrTi and CrC intermetallic phases. This is consistent with the high thermal of the TIG process, which allows chromium from the substrate to react with the TiC nanoparticles. Although these phases are too small to be individually distinguished in FESEM without EDX, the presence is confirmed by the sharp peaks in XRD analysis and the high hardness values recorded in the nanocomposite coating layer. Increased pulse frequencies enhance deposition efficiency, producing denser coatings with TiC nanoparticles distribution. This trend was supported by prior research conducted by Vypana et al. [17], who investigated the effects of direct current micro-pulsing, including variations in pulse frequency, on the microstructure and mechanical properties of TIG-welded Ti-6Al-4V alloy. The results demonstrate that higher pulse frequencies result in grain refinement and enhanced mechanical properties, providing significant insights into the optimization of pulse parameters in TIG processes.

3.2 Effect of pulse frequency on the mechanical properties

3.2.1 Micro Vickers hardness

Microhardness assessments were performed across the cross-section, from the upper surface of the nanocomposite coating to the substrate. These assessments were carried out to investigate the role and effectiveness of TiC nanoparticles in influencing the hardness profile. The measurements were performed under a constant current of 140 A and varying pulse frequencies (15-25 PPS), as illustrated in Figure 6. The result offers valuable insights into the influence of pulse frequency adjustments on microhardness distribution and the contributions of TiC nanoparticles deposition onto the substrate material. This detailed profile enables a better understanding of the correlation between the properties of the nanocomposite coating and the process parameters.

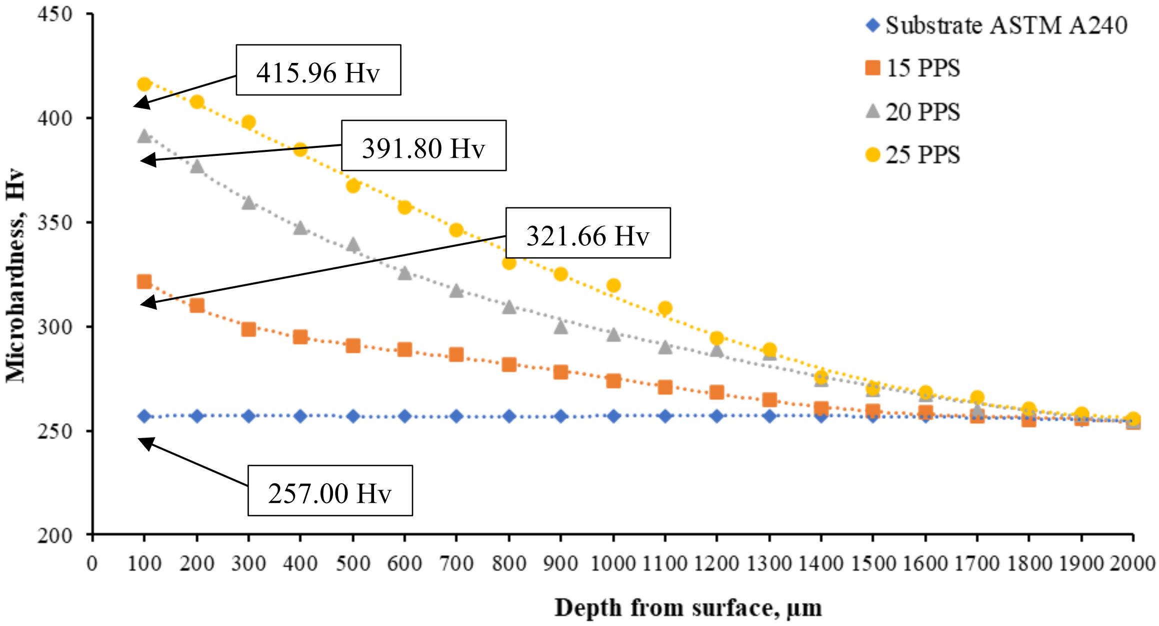

Figure 6: Microhardness distributions along with the depth direction in the cross-section of the nanocomposite coatings at TIG different pulse frequency settings

The results demonstrate a significant increase in surface hardness as the pulse frequency is progressively raised during the TIG welding process. At a pulse frequency of 15 PPS, the hardness is measured at 321.66 Hv. While the TiC nanocomposite coating provides reinforcement to the surface, the bonding with the substrate remains suboptimal, leading to moderately enhanced hardness. This condition reflects limited TiC nanoparticles penetration and uneven dispersion within the substrate. Meanwhile, as the pulse frequency increases to 20 PPS, the microhardness shows a notable improvement, reaching 391.80 Hv, representing an increase of approximately 21.8 % compared to 15

PPS. The higher pulse frequency facilitates more effective deposition of TiC nanoparticles, ensuring better reinforcement of the surface layer. This improvement is attributed to enhanced bonding more uniform particle distribution between the nanoparticles and the substrate. The coating becomes structurally stronger, providing greater wear resistance and mechanical stability.

Moreover, at the maximum pulse frequency of 25 PPS, the surface hardness achieves its highest value of 415.96 Hv, corresponding to an additional improvement of 29.3 %. This condition results from refined TiC nanoparticles dispersion, which produces a highly compact and uniform layer. A distribution of deeper penetration of the TiC nanoparticles onto the substrate is achieved at higher pulse frequencies. This is evidenced by the increase in the coating thickness layer, which reaches a maximum depth of 1.78 mm at 25 PPS (as shown in Figure 4). The cross-sectional analysis confirms that the TiC nanoparticles are distributed throughout the entire depth of the modified zone. This correlation suggests that the higher pulse frequency provides sufficient heat to facilitate the migration of nanoparticles from the surface into the deeper regions of the substrate.

The results clearly demonstrate that higher pulse frequencies enhance the surface microhardness and overall coating performance, primarily due to improved TiC nanoparticles deposition and dispersion. These findings support from previous study by Yu et al. [18] which revealed that higher pulse frequencies notably enhanced microhardness, driven by a finer distribution of TiC particles and improved dispersion strengthening. Consequently, pulse frequency is crucial in optimizing the hardness and overall performance of these coatings.

3.3 Effect of pulse frequency on the tribological properties

3.3.1 Coefficient of friction

The CoF is a key parameter for evaluating the tribological performance of TiC nanocomposite coatings on ASTM A240. The findings reveal a significant reduction in CoF as the pulse frequency increases during the TIG torch process, underscoring the critical role of TiC nanoparticles distribution and surface hardness in minimizing frictional resistance as presented in Figure 7.

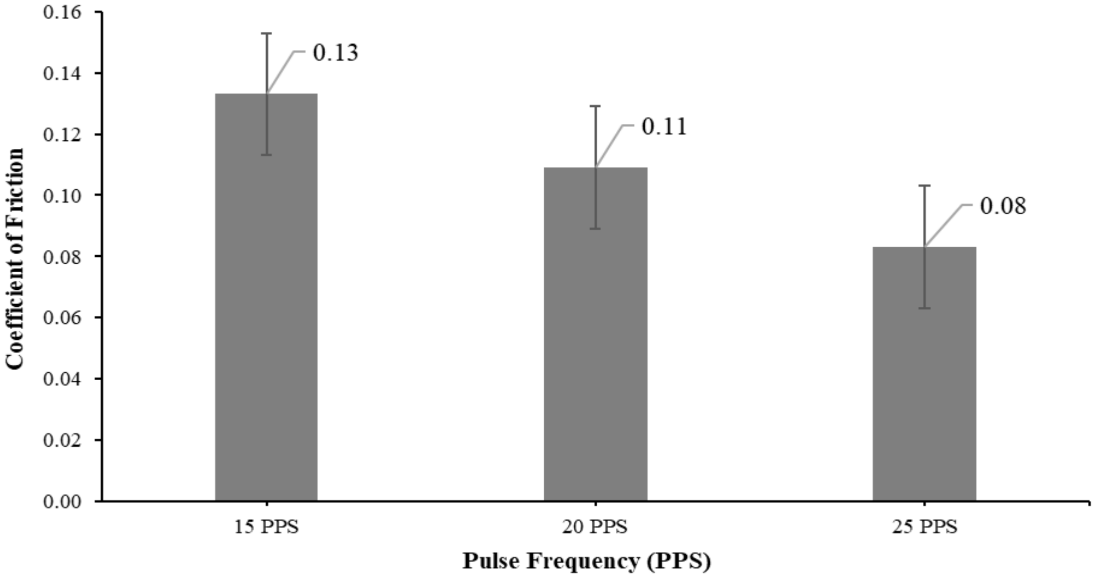

Figure 7: CoF of TiC nanocomposite coating at different TIG pulse frequency settings

At a pulse frequency of 15 PPS, the CoF is measured at 0.13, indicating higher frictional resistance. This is attributed to moderate hardness and uneven nanoparticles distribution within the surface layer. Consequently, surface roughness increases, promoting greater friction during sliding interactions. The relatively high CoF at this frequency reflects suboptimal tribological performance, which could lead to increased wear in applications such as automotive components or industrial machinery. However, as the pulse frequency increases to 20 PPS, the CoF decreases to 0.11, representing a 15.38 % reduction. The improvement in CoF is directly linked to enhanced nanoparticles dispersion and increased surface hardness, which reduces material deformation and frictional resistance. This provides sufficient thermal energy for better dispersion, resulting in smoother surface interactions and improved wear resistance.

Subsequently, at the highest pulse frequency of 25 PPS, the CoF drops further to 0.08, marking the lowest value observed in this study. This represents a 27.27 % reduction, and the rapid pulsing ensures optimal nanoparticles distribution and surface reinforcement, creating a dense and uniform structure that minimizes surface deformation during sliding. Additionally, enhanced smoothness at this frequency contributes to superior tribological behavior, making the nanocomposite coating more suitable for applications requiring low friction and high durability.

The inverse relationship between CoF and pulse frequency is evident, with higher pulse frequencies improving the surface characteristics and thereby reducing friction. This reduction is primarily driven by the combined effects of increased hardness and refined microstructural properties, which enhance surface integrity and reduce the likelihood of wear-related failures. The trend aligns with previous work by Wu et al. [19] demonstrated that with the increase in pulse frequency, the friction coefficient of coatings increases, and the average friction coefficient of coatings solidified at different pulse frequencies. This is attributed to the high hardness of the coating solidified, which endows the coating with good resistance to deformation under high load during the test.

3.3.2 Worn surface

The FESEM micrographs (Figure 8) illustrate the worn surface areas of TiC nanocomposite coatings subjected to a reciprocating wear test at different pulse frequencies as shown in Figures 8(a), 8(b) and 8(c). The observation of this micrograph's emphasizes the variations in wear mechanisms that correspond to the influence of pulse frequency on surface characteristics such as hardness and particle distribution. The worn surface at 15 PPS as shown in Figure 8(a) exhibits shallow ploughing accompanied by the presence of micro-grooves, as visible in the micrograph. These features suggest a combination of abrasive wear mechanisms and surface roughness due to unfavorable TiC nanoparticles dispersion at this lower pulse frequency. The reduced energy input leads to less effective deposition and bonding of TiC nanoparticles, resulting in a softer surface layer with moderate reinforcement. This promotes material removal during sliding, resulting in surface grooves that imply reduced wear resistance.

Meanwhile, at 20 PPS (Figure 8(b)), the worn surface shows shallow ploughing, with fewer micro-grooves. The reduced severity of wear features reflects an improvement in surface hardness and tribological performance. This provides better molten pool agitation during the welding process, resulting in a more uniform distribution of TiC nanoparticles and enhanced bonding with the substrate. This refinement minimizes material deformation under sliding friction, leading to improved wear resistance and less pronounced surface damage. The worn surface at pulse frequency of 25 PPS displays only shallow grooves as depicted in Figure 8(c), with minimal evidence of ploughing. This observation suggests the dominant wear mechanism has shifted toward mild abrasive wear, indicative of significant improvements in hardness and surface integrity. The highest pulse frequency produces the best parameter for the TiC nanoparticle dispersion and structural uniformity, creating a dense and robust coating layer. Consequently, the reinforced surface resists material removal more effectively, resulting in smoother wear tracks with minimal damage. The uniform deposition of TiC nanoparticles further reduces friction, enhancing both wear resistance and overall tribological performance.

The micrographs demonstrate that as the pulse frequency increases, the severity of wear features decreases, reflecting the critical role of pulse frequency in determining the surface characteristics of TiC nanocomposite coatings. At lower frequencies, insufficient energy input results in softer coatings prone to abrasive wear. Conversely, higher pulse frequencies enhance nanoparticles distribution and hardness, minimizing wear features and improving surface durability. These findings align with the previous study by Paijan et al. [20], which investigated the deposition of SiC coating using the TIG torch method. The results revealed that SiC particles embedded in the DSS surface were strongly bonded to the substrate material, significantly enhancing wear resistance. Consequently, the hard surface layer in the SiC-DSS reinforced surface exhibited increased durability and resisted detachment during reciprocating wear tests. Moreover, the best-performing sample demonstrated smooth striation conditions, indicating superior performance compared to the other tested samples.

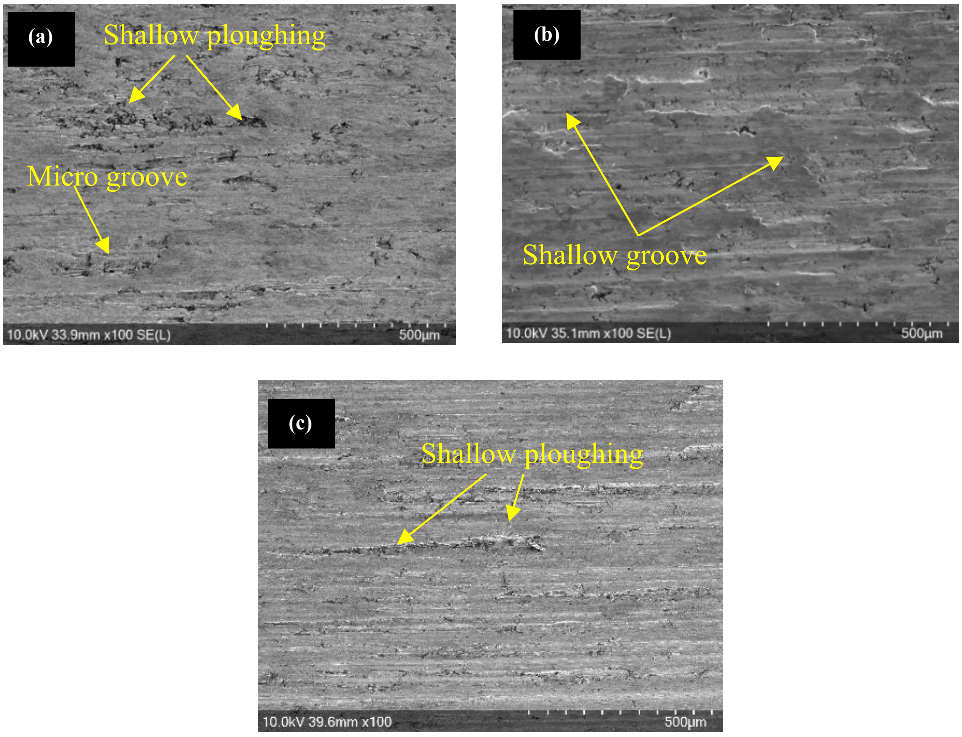

Figure 8: FESEM micrographs of worn surface area after reciprocating wear test at different pulse frequency settings (a) 15 PPS, (b) 20 PPS and (c) 25 PPS

4. CONCLUSIONS

This study highlights the success of surface enhancement of ASTM A240 steel through the deposition of 5 nm TiC nanoparticles via the TIG torch method. The modified surface exhibited substantial improvements in hardness and wear resistance, with pulse frequency playing a critical role in determining coating characteristics. The principal findings are summarized as follows:

1) A maximum coating thickness of 1.78 mm was achieved at 25 PPS, attributed to the optimal energy input facilitating uniform nanoparticles deposition. In contrast, lower pulse frequencies (15–20 PPS) yielded thinner coatings, ranging from 1.34 mm to 1.62 mm, due to insufficient energy for complete particle integration.
2) The sample processed at 25 PPS exhibited the highest microhardness (415.96 Hv), resulting from improved TiC nanoparticle dispersion and stronger interfacial bonding within the nanocomposite coating matrix. Higher pulse frequencies facilitate deeper TiC incorporation and improved metallurgical bonding, which results in improvement for hardness and wear resistance.

3) The lowest CoF (0.08) was recorded for the 25 PPS sample, which displayed a smoother surface morphology with minimal wear grooves and shallow abrasion marks. This reduction in frictional resistance underscores the coating's effectiveness in minimizing surface degradation under sliding conditions.

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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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