Nabochenko Vasyl, PhD Student, Department of Technical Mechanics and Engineering Graphics, Lviv Polytechnic National University, Ukraine, Lviv, https//orcid.org/0009-0002-8809-3602

TITANIUM CARBIDE SURFACE ENGINEERING: REVIEW OF RECENT ADVANCES IN APPLICATION METHODS AND TECHNIQUES

Abstract

Titanium carbide remains a cornerstone of modern surface engineering, distinguished by its face-centered cubic NaCl-type crystal structure and a suite of exceptional refractory properties. With a high melting point of 3067°C, an elastic modulus between 410 and 450 GPa, and a hardness reaching 3200 HV, TiC is uniquely positioned to enhance the durability of substrates in demanding industrial environments. This review article provides a systematic and comprehensive survey of the latest advancements in TiC deposition and application techniques, spanning literature of recent years. By investigating the intersection of microstructural tailoring and tribological performance, the paper offers a high-level roadmap for researchers aiming to mitigate TiC's inherent brittleness while maximizing its protective capabilities.

The investigation encompasses a broad spectrum of sophisticated application methods, categorizing them by their deposition mechanisms and resulting coating characteristics. Key techniques analyzed include diffusion and in-situ methods, such as the In-situ Solid-phase Diffusion Method, which leverages cast iron as a carbon source to create gradient TiC-Fe coatings on titanium substrates with a volume fraction exceeding 95% [1]. Thermal and plasma deposition processes, such as High-Velocity Oxy-Fuel thermal spraying, are evaluated for their efficacy in protecting SS316 steel, alongside Air Pulsed

Plasma Deposition, which utilizes electro-thermal axial accelerators to synthesize particle-reinforced metal matrix composites. Significant attention is paid to laser and arc-based technologies, including laser cladding and Tungsten Inert Gas welding, which are noted for their industrial scalability and ability to refine substrate microstructures from pearlite to high-hardness phases [2]. Advanced sputtering and vapor deposition techniques are also explored, such as Dual-Ion Beam Sputtering for nano-coatings and Chemical Vapor Deposition for complex geometries, highlighting the formation of metastable TiC phases and supersaturated solid solutions [3].

The article further provides a comparative analysis of mechanical performance across diverse substrates, including Ti6Al4V alloys, AISI 1020 steel, and YG8 cemented carbides. It quantifies the influence of process parameters such as discharge voltages, pulse rates, and vacuum levels on interfacial adhesion and wear volume reduction. For instance, specific chemical reactions such as $2CO\rightarrow CO_{2}\uparrow+[C]$ and $8Ti+5[C]\longrightarrow Ti_{8}C_{5}$ are identified as critical mechanisms in salt bath carburizing that lead to a 55.9% reduction in friction coefficients.

By synthesizing these findings into a comparative framework, the review highlights the trade-offs between high-conformality techniques and high-speed scalable methods. This work serves as a short review summarizing recent advances in TiC surface engineering strategies to extend the service life of critical components in the aerospace, biomedical, and manufacturing sectors.

Keywords: Titanium Carbide, Surface Engineering, Laser Cladding, Diffusion Coatings, Hardness, Wear Resistance, Microstructure.

Introduction

Titanium carbide is a refractory transition metal carbide with a face-centered cubic NaCl-type crystal structure[1], exhibits properties such as high

hardness (up to 3200 HV), elevated melting point (3067°C), substantial elastic modulus (410–450 GPa), low density (4.93 g/cm³), good thermal and chemical stability, low friction coefficient, and great wear and corrosion resistance, making it a good option for enhancing the durability of substrates in demanding environments, though its relative brittleness and lower fracture toughness compared to metals pose challenges in high-impact applications [2], [3]. TiC's coatings are widely adopted in modern industries, such as cutting tools and molds in manufacturing for extended tool life and reduced friction [2], [3], aerospace components for lightweight high-temperature performance [4], biomedical implants on titanium alloys like Ti6Al4V to improve tribocorrosion resistance and biocompatibility [3], [5], automotive and marine parts for abrasion protection [3], and chemical processing equipment for oxidation and corrosion mitigation [2]. This review systematically surveys the advancements in TiC surface engineering, encompassing a detailed analysis of conventional and cutting-edge deposition techniques, microstructural characterization, and the resulting enhancements in mechanical and tribological performance [3].

Methodology

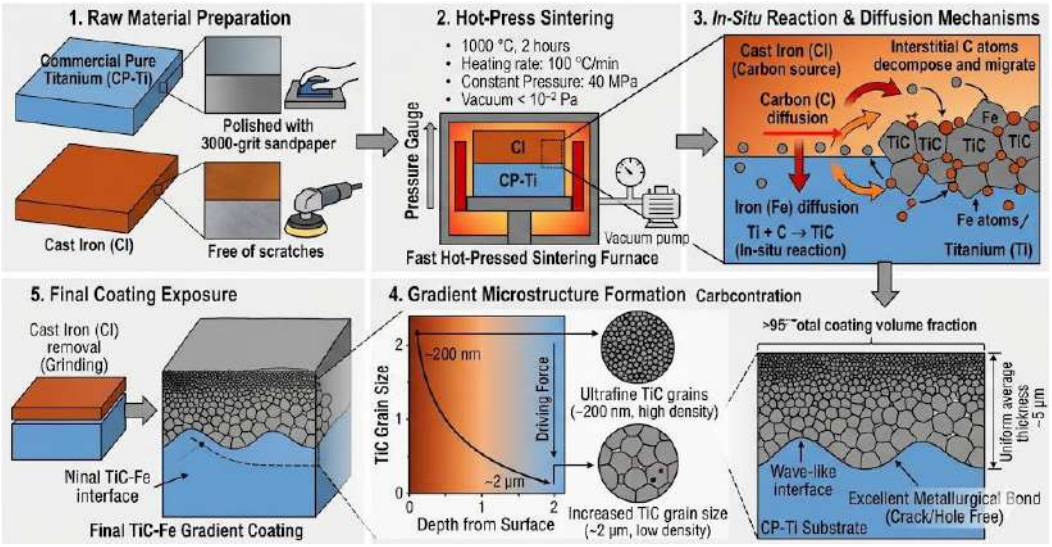
This review was conducted by systematically analyzing peer-reviewed literature, including journal articles and conference proceedings, published between 2000 and 2026, with a focus on titanium carbide coating methodologies, property enhancements, and industrial applications. The search strategy employed keywords such as "titanium carbide coatings," "TiC deposition techniques" (e.g., CVD, PVD), "mechanical properties of TiC," "tribological performance," and "surface modification." The gathered information was then critically synthesized to identify emerging trends, significant breakthroughs, and existing challenges in the field. AI tools were used to assist in the preliminary screening and thematic categorization of the extensive literature. Manual review was conducted to verify and edit any AI-generated content for accuracy and relevance.

Results

Significant research attention has been paid to laser cladding for TiC coatings, while techniques such as CVD and PVD are also critical for tailoring TiC coatings to specific industrial requirements[3], [6]. New advances continue to emerge in these areas as well[6]. This review covers only select advances of particular interest to the authors, with a breakdown by technique provided below. Other emerging vectors, such as high-entropy carbides and metal matrix composites, will be addressed later in the discussion.

The ISDM (In-situ Solid-phase Diffusion Method) was utilized to fabricate a TiC–Fe gradient coating on a pure titanium substrate using cast iron as the carbon source [7]. The process was conducted at a temperature of 1000 °C for a duration of 2 hours under a constant pressure of 40 MPa and a vacuum degree lower than 10^{-2} Pa [7]. The resulting coating achieved an average thickness of approximately 5 μm and was characterized by a TiC volume fraction exceeding 95% [7]. Key results included a superior surface hardness of 42.9 ± 2.6 GPa and an elastic modulus of 557.4 ± 10.3 GPa, which respectively represent a 7.4-fold and 2.4-fold increase compared to the cast iron reference [7]. Interfacial adhesion strength was measured to be greater than 225 ± 10 MPa, facilitated by the gradient transition of the microstructure and excellent atomic-scale bonding at the coating/substrate interface[7]. While the treatment was shown to significantly improve load-bearing capacity and reduce residual indentation depth, a specific numerical value for the friction coefficient was not explicitly reported in the results, although the gradient design was specifically implemented to address poor wear resistance [7]. The coating exhibited inward grain growth, with TiC grain sizes increasing from 200 nm at the surface to 2 μm towards the substrate, leading to a fracture mechanism transition from intergranular to transgranular along the coating thickness [7].

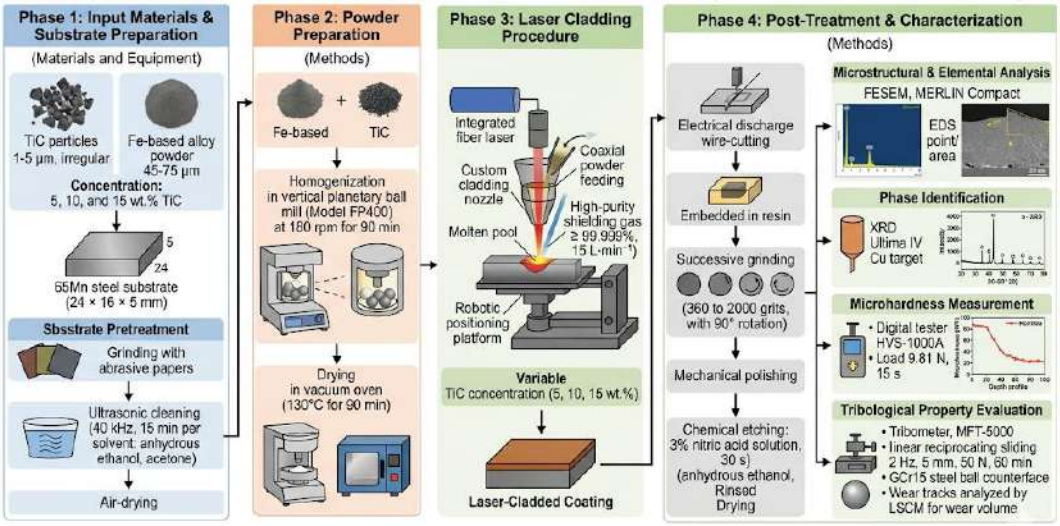
Figure 1. ISDM process illustration



Laser cladding process was utilized to synthesize TiC–Fe-based composite coatings on a 65Mn steel substrate to enhance its surface hardness and wear resistance [6]. Numerical simulations revealed that the addition of 15 wt.% TiC induced surface temperatures reaching approximately 3449 °C, creating localized thermal islands that intensified cooling rates and promoted high-hardness phases such as $(Cr, Fe)_7C_3$ [6]. The process successfully mitigated crack formation through the uniform dispersion of TiC particles, which also refined the microstructure from pearlite to feather-like bainite [6]. Significant improvements in mechanical properties were achieved; specifically, the 15 wt.% TiC coating yielded an average microhardness of 890 HV and a peak of 912.24 HV nearly 3.9 times the substrate hardness of 230.3 HV with the maximum hardness layer located approximately 0.6 mm beneath the surface [6]. Regarding tribological performance, the substrate exhibited a coefficient of friction of 0.4399, while the 5 wt.% TiC coating demonstrated the lowest coefficient at 0.3811 and the 15 wt.% TiC coating showed a coefficient of 0.4468 with improved frictional stability [6]. The 15 wt.% TiC variant achieved the most favorable results with a minimal wear

mass loss of 0.1 mg and a specific wear track depth of 82 μm and width of 800 μm [6].

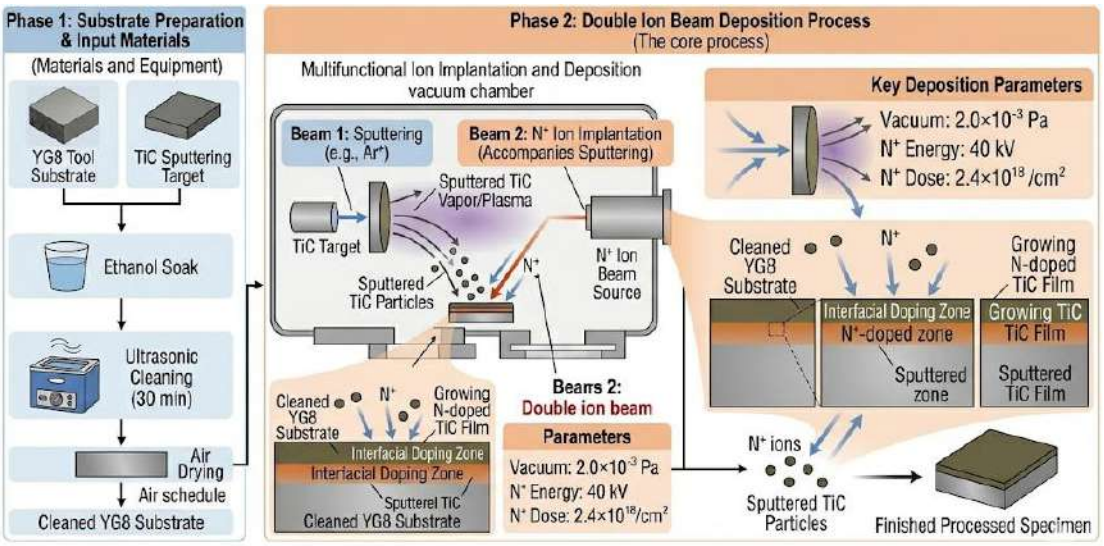
Figure 2. Laser cladding process illustration



Dual-Ion Beam Sputtering deposition by Dou Zhongyu et al., a TiC nano-coating was prepared on the surface of YG8 cemented carbide substrate where N-ion implantation was utilized to assist the sputtering process [8]. This non-thermal equilibrium process allowed for the precise adjustment of ion dose and energy to create a highly supersaturated solid solution and metastable TiC phase, specifically exhibiting, and crystal surface diffraction peaks [8]. The resulting surface modification significantly enhanced the mechanical properties of the substrate, increasing the surface hardness from an untreated value of 1672 HV to 2238 HV [8]. Tribological evaluations conducted under dry friction conditions using a 50N load at a speed of 100 r/min with an aluminum oxide ball demonstrated that the TiC coating effectively reduced the friction coefficient and wear volume compared to the uncoated tool [8]. Furthermore, the deposition improved the anti-crack ability and reduced surface roughness by minimizing fracture surface cracks and scratches, ultimately leading to higher bonding

strength and extended tool service life [8]. Although the specific processing temperature was not detailed, the injection process successfully bypassed traditional solid solubility limits to form a uniform coating with superior wear resistance [8].

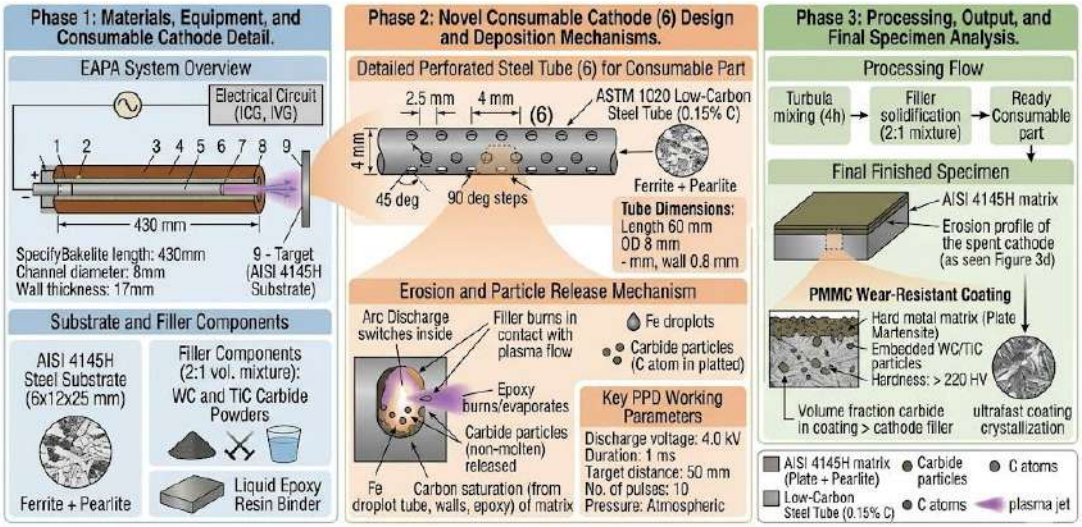
Figure 3. Dual-Ion Beam sputtering deposition process



Air pulsed plasma deposition employs an electro-thermal axial plasma accelerator with a consumable cathode [9]. The process involves 10 plasma pulses at a discharge voltage of 4.0 kV, a discharge duration of 1 ms, and atmospheric pressure[9]. Middle-carbon steel substrates with an initial "Ferrite + Pearlite" structure and hardness of 220 HV were used[9]. The resulting particle-reinforced metal matrix composite coating, composed of (TiC + WC) in a hardened steel matrix, achieved a thickness of 24–31 μm [9]. Hardness values ranged from 500–1044 HV in the matrix and 1516–2029 HV in the carbide particles [9]. The coefficient of friction was 0.52 against a 100Cr6 ball and 0.10 against a SiC ball [9]. Deposition occurred under atmospheric conditions [9], with tribological testing at ambient temperature[9]. Wear resistance improved significantly, with volumetric wear reduced by 4.4 times against 100Cr6 steel and by 16 times against SiC compared to the substrate [9]. The structure featured successful direct plasma

transfer of carbides without substantial melting into a matrix of 57 vol.% austenite and 43 vol.% martensite [9]. Minor oxide phases formed during the process acted as a solid lubricant, inhibiting adhesion and lowering the coefficient of friction[9].

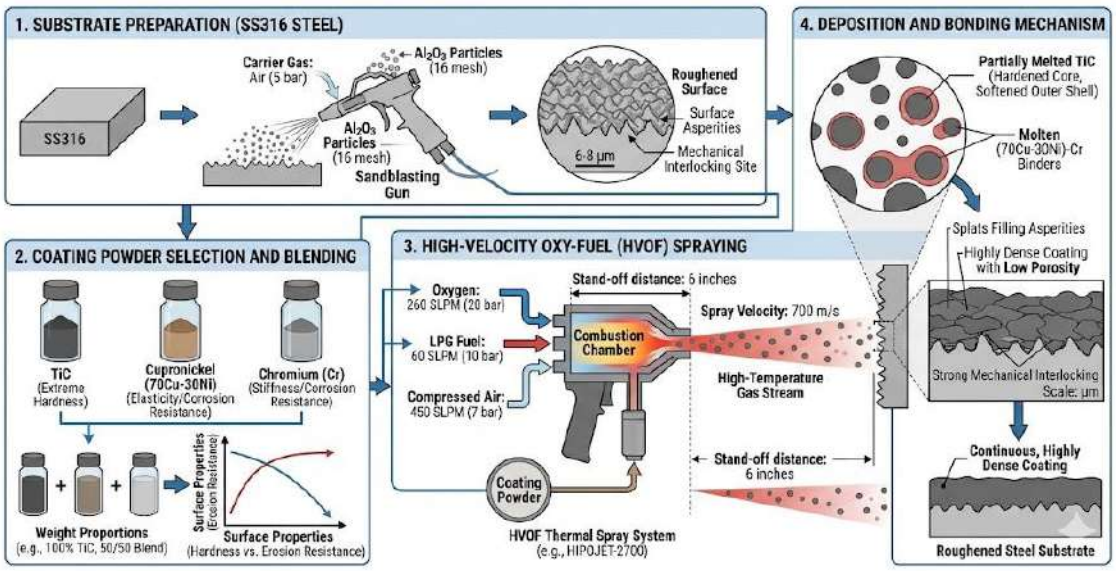
Figure 4. Air pulsed plasma deposition illustration



HVOF (High Velocity Oxy-Fuel) thermal spraying was utilized to deposit composite coatings consisting of Titanium Carbide with (70Cu-30Ni)-Cr binders onto SS316 stainless steel substrates to enhance cavitation erosion resistance [10]. Prior to deposition, the substrate was sand-blasted at 5 bar pressure with Al2O3 particles to achieve a surface roughness of 6–8 µm for optimal mechanical interlocking [10]. The process utilized a high-temperature gas stream to deposit powders in three specific proportions: pure TiC, a TiC+50%(70Cu-30Ni)-Cr blend, and pure (70Cu-30Ni)-Cr [10]. Characterization revealed that the pure TiC coating achieved an average microhardness of 1154 ± 21 HV9.81N and a thickness of 229 ± 21 µm with 1.45% porosity [10]. The TiC+50%(70Cu-30Ni)-Cr composite reached a maximum layer thickness of 281 ± 28 µm, a microhardness of 845 ± 35 HV9.81N, and a porosity of 1.87% [10]. The pure (70Cu-30Ni)-Cr coating exhibited the lowest microhardness at 407 ± 16 HV9.81N and a thickness of 223 ± 19 µm [10]. While specific friction coefficients and gas temperatures were not quantified, the experimental results demonstrated that the

TiC+50%(70Cu-30Ni)-Cr composite was the most effective at resisting cavitation erosion under critical test conditions, including stream velocities of 40 m/s and an angle of attack of 60° [10].

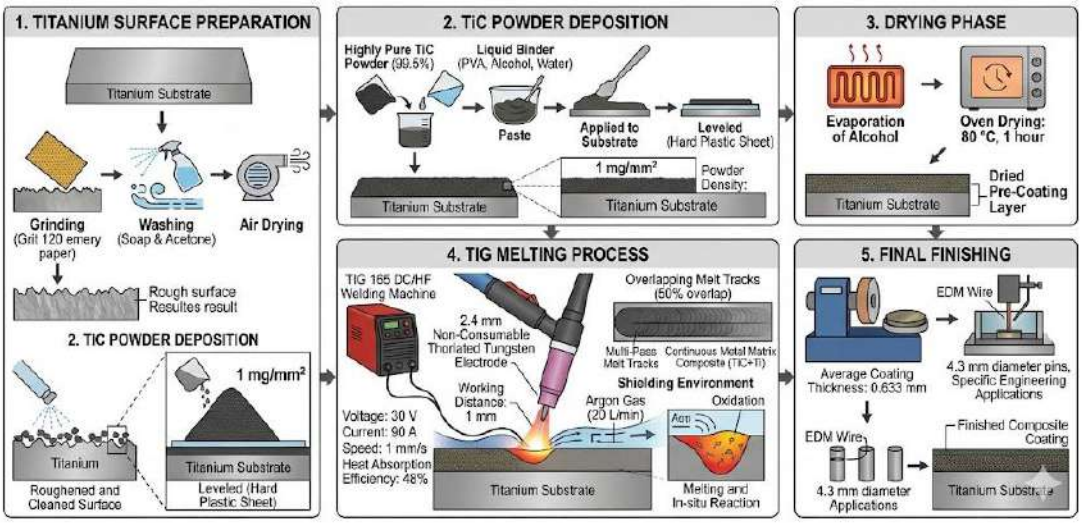
Figure 5. HVOF process illustration



TIG (Tungsten Inert Gas) welding torch melting process was employed to synthesize titanium carbide composite coatings on a commercially pure titanium substrate [4]. The coating material consisted of 99.5% pure TiC powder with a particle size between 45 and 100 microns, applied as a paste and pre-heated in an oven at 80°C for one hour to ensure moisture removal [4]. The deposition process utilized a 2.4 mm diameter thoriated tungsten electrode at a working distance of 1 mm, operating at 30 V and 90 A with a table traveling speed of 1 mm/s [4]. Argon shielding gas was supplied at 20 L/min to minimize oxidation during the melting phase, which was characterized by a 48% heat absorption efficiency [4]. Post-processing results indicated a finished coating layer thickness of 0.633 mm and a Vickers hardness of 383 HV5, with an average surface roughness (R_a) of 0.367 µm [4],[4]. Performance evaluations conducted between 0.38 and 1.5 m/s sliding speeds under loads of 20 to 50 N showed that while TiC is inherently characterized by a low coefficient of friction, increased operational intensity led to elevated flash temperatures and frictional heating that influenced wear transitions

[4]. The coatings successfully achieved a "very mild" wear rate - defined as less than or equal to $0.1 \times 10^{-12} \text{ m}^3\text{ m}^{-1}$- under most test conditions due to the formation of protective mechanically mixed and iron oxide layers [4].

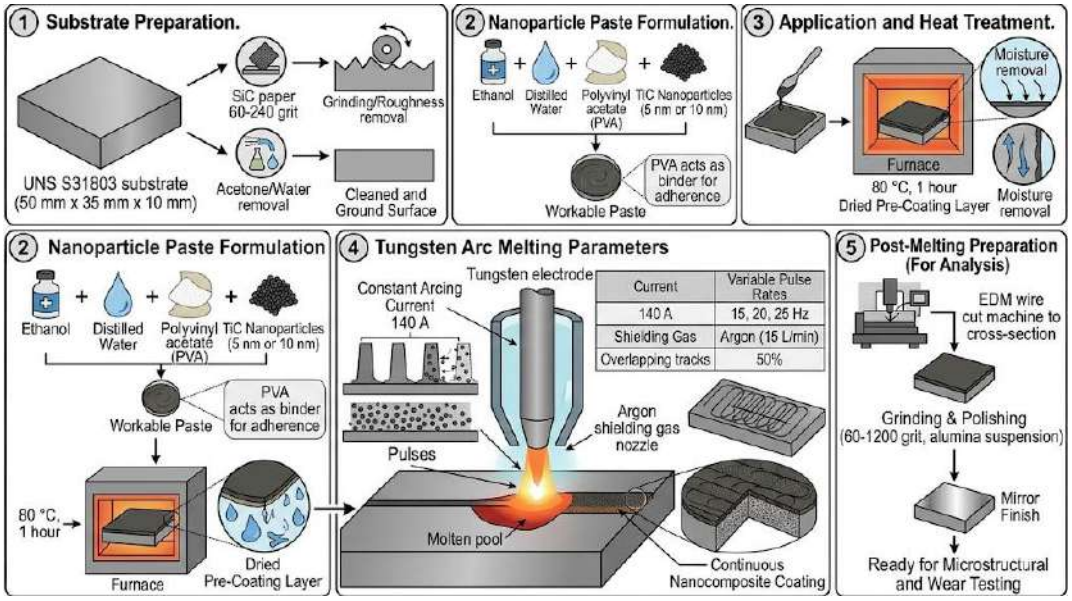
Figure 6. TIG welding TiC coating process illustration



Tungsten arc melting was employed as the surface modification process to deposit TiC nanoparticles, in sizes of 5 nm and 10 nm, onto a UNS S31803 duplex stainless steel substrate [11]. The methodology involved pre-treating a TiC paste at 80 °C for one hour before arc melting at a constant current of 140 A with varying pulse rates of 15 Hz, 20 Hz, and 25 Hz under a 15 L/min argon shielding gas flow using a 50% overlapping track scheme [11]. Some improvements in surface properties were achieved, with the 5 nm nanoparticle deposition at a 25 Hz pulse rate yielding a maximum microhardness of 415.96 HV, representing a substantial increase over the 259 HV substrate baseline [11]. The highest wear resistance was achieved with 5 nm at 25 Hz with a wear rate of 1.01 x 10^{-5} mm^3/Nm with the superior ability to reduce wear rates and enhance surface hardness among larger particles[11]. While specific friction coefficient values were not explicitly quantified, the optimal 25 Hz pulse rate facilitated a maximum elemental TiC concentration of 91.60% and enhanced penetration of nanoparticles into the substrate depth profile, effectively reducing material removal and resulting in

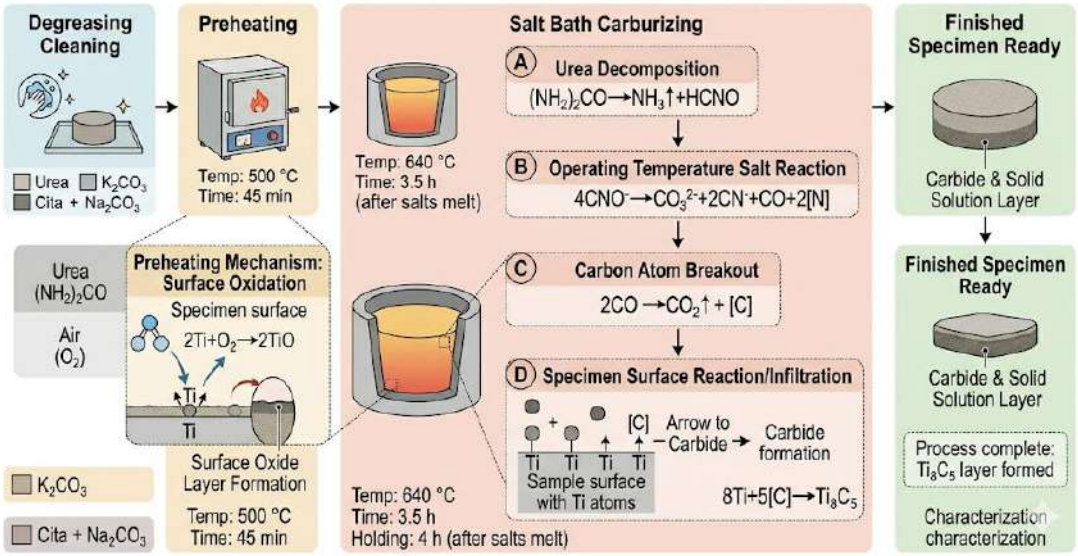
shallow worn grooves rather than the deep spalling craters and intensive abrasive wear observed in less optimal configurations like 10 nm particles at 20 Hz [11]

Figure 7. Tungsten arc melting process illustration



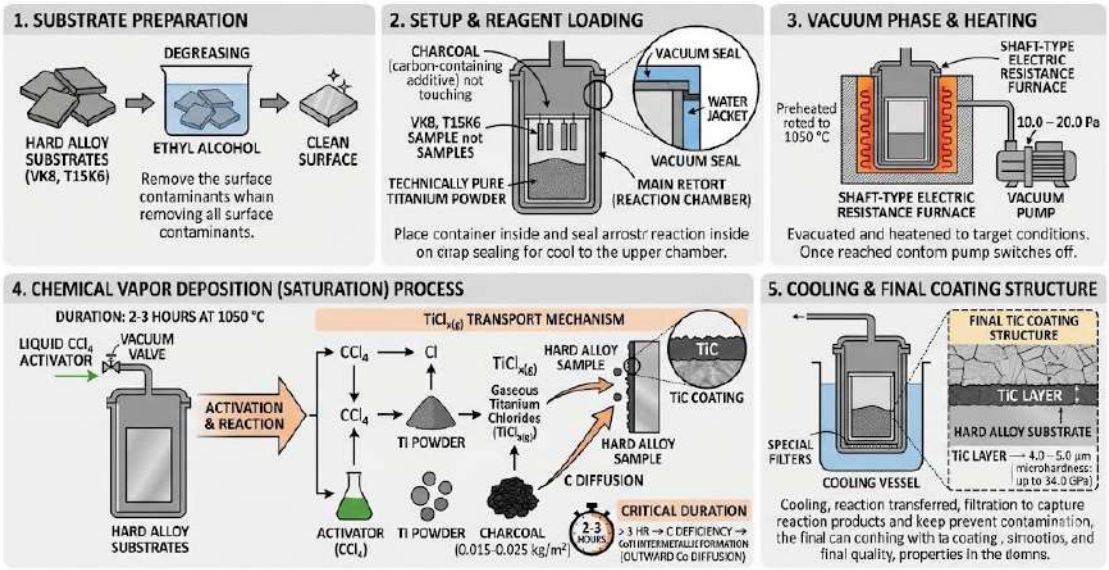
Salt bath carburizing at a low temperature of 640 °C was performed on a Ti6Al4V alloy substrate to synthesize a titanium carbide thin film for improved tribological performance [5]. The procedure included a 45-minute preheating phase at 500 °C followed by a 3.5-hour immersion in a salt bath composed of urea and carbonates, which facilitated carbon infiltration and the formation of a high-hardness Ti8C5 carbide phase [5]. This surface treatment increased the substrate hardness from an initial 370.65 HV to a peak of 953.28 HV, with the hardness profile indicating an effective infiltrated layer depth of approximately 40 μm before the values stabilized at the matrix hardness [5],[5]. Results from dry friction tests conducted at room temperature revealed that the friction coefficient was reduced by 55.9%, dropping from 0.34 to 0.15 under a 300 N load [5]. Additionally, the treatment significantly enhanced wear resistance, achieving a mass wear loss that was 29 times lower than that of the untreated Ti6Al4V alloy when tested under a 100 N load[5].

Figure 8. Salt bath carburizing process illustration



CVD Titanizing via diffusion metallization was performed on VK8 and T15K6 hard alloy substrates to form protective carbide coatings [12]. The process was conducted at a temperature of 1050 °C for a duration of 2 to 3 hours within a closed reaction chamber under reduced pressure, utilizing technically pure titanium powder, a carbon-containing additive, and carbon tetrachloride (CCl_4) as a chemical activator [12]. Results achieved under optimal conditions (2 hours of saturation) include the formation of a titanium carbide layer with a thickness of 4.0–5.0 μm and a high microhardness ranging from 33.0 GPa for VK8 to 34.0 GPa for T15K6 [12]. While a significant improvement in wear resistance was observed, increasing the saturation time to 3 hours or more led to the formation of a CoTi intermetallic surface layer and a carbon-depleted sublayer containing the Co_3W_3C phase, which can negatively impact the coating's properties [12]. Although specific friction coefficient values were not explicitly detailed, the study confirmed that the resulting TiC layer effectively enhances tool material performance by providing a well-defined, hard boundary with the substrate [12].

Figure 9. CVD CarboTitanizing process illustration



Gas carburizing followed by **thermo-reactive diffusion** salt bath processing was employed to deposit a titanium carbide coating onto an AISI 1020 steel substrate [13]. The process initiated with gas carburizing at 950 °C for 15 hours at a pressure of 200–300 Pa using methane to enrich the surface carbon content, after which TRD was performed in a salt bath at 900 °C for 3 hours [13]. The resulting coating achieved a thickness of 7.5 ± 0.3 μm and an average surface micro-hardness of 1885 ± 121 HV0.025, which represents a significant enhancement over the 185 ± 21 HV0.025 hardness of the bare substrate [13]. Tribological evaluations indicated a friction coefficient ranging from 0.45 to 0.56, which averaged 0.49 for the duplex-treated sample, and a high critical adhesion failure load of approximately 52 N [13]. Furthermore, this duplex treatment resulted in a 78% reduction in specific wear volume loss compared to the untreated low-carbon steel [13].

Figure 10. TRD with pre gas carburizing process illustration

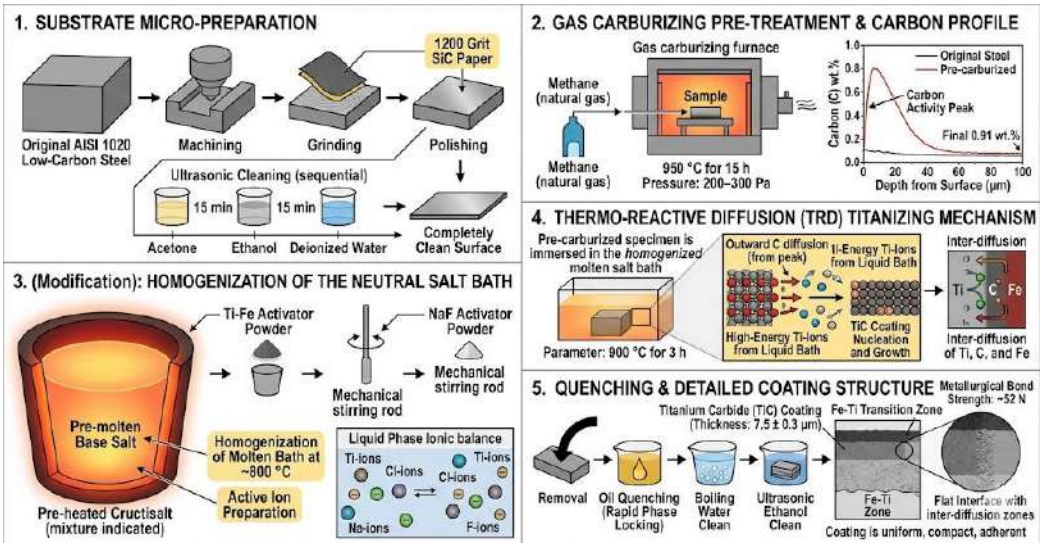


Table 1 Summary comparison ok key characteristics

Process	Substrate	Specs	Results	Ref.
ISDM	Commercial Pure Titanium (CP-Ti) and Cast Iron	1000 °C; 2 hours; 40 MPa constant pressure; Vacuum $< 10^{-2}$ Pa.	Thickness: ~5 µm; Hardness: 16.2–42.9 GPa; El. modulus: 557.4 GPa Adhesion: > 225 MPa; TiC Vol%: > 95%.	[5]
Laser cladding	65Mn steel	Cleaning: 40 kHz ultrasonic (15 min/solvent). Powder: TiC (5, 10, 15 wt.%) + Fe-based alloy. Milling: 180 rpm / 90 min. Drying: 130°C / 90 min. Atmosphere: Ar gas (≥ 99.999%) at 15 L/min.	**Microhardness:** 890 HV (Avg), 912.24 HV (Peak); **CoF:** 0.3811–0.4468; **Hardness depth:** 0.6 mm	[6]
Dual-Ion Beam Sputtering	YG8 cemented carbide	pre-coated with PVD-TIC **Cleaning:** Aqueous ethanol ultrasonic (30 min). **Vacuum:** 2.0×10^{-3} Pa. **N-Ion Injection Energy:** 40 kV. **Injected Dose:**	Microhardness: 2238 HV (Substrate: 1672 HV). Avg CoF: 0.283 (Substrate: 0.482). Wear Mark Area: 90.535 μm^2 (97.6% reduction vs	[7]

		$2.4 \times 10^{18}/cm^2$	substrate). Friction Load: 50 N at 100 **r/min.**	
Air pulsed plasma deposition	AISI 4145H	10 pulses; 4.0 kV discharge; 1 ms duration; Atmospheric pressure.	Thickness**:** 24–31 µm; Hardness**:** 1516–2029 HV (carbides); CoF**:** 0.10 (vs SiC) to 0.52 (vs 100Cr6). TiC + WC	[8]
HVOF thermal spraying	SS316 stainless steel	Pre-treatment: Sand-blasting (Al_2O_3, 16 mesh) at 5 bar for 6–8 μm roughness. Pure TiC or TiC+NiCr powders. O_2 (260 SLPM, 7 bar); LPG Fuel (60 SLPM, 10 bar); Air (450 SLPM, 6 bar); N_2 carrier (20 SCFH) Spray Velocity: 700 m/s; Distance: 6 inches	Pure TiC Coating: Thickness 229 ± 21 μm**;** Microhardness 1154 ± 21 $HV_{9.81N}$**;** Porosity 1.45 ± 0.08**%.** TiC+50% Binder: Thickness 281 ± 28 μm**;** Microhardness 845 ± 35 $HV_{9.81N}$**;** Porosity 1.87 ± 0.09**%.** Max Erosion Conditions: 40 m/s stream velocity, 8 cm SOD, and 60˚ attack angle.	[9]
TIG welding	Commercial Pure Titanium	30 V; 90 A; 1 mm/s speed; Argon gas (20 L/min); Pre-heat: 80 °C (1h).	Thickness**:** 0.633 mm; Microhardness**:** 383 HV5; Roughness **(R_a):** 0.367 µm; Wear rate**:** $\leq 0.1 \times 10^{-12} m^3 m^{-1}$.	[3]
Tungsten arc melting	UNS S31803 duplex stainless steel	140 A; 15–25 Hz pulses; Argon gas (15 L/min); Pre-heat: 80 °C (1h).	Max Microhardness**:** 415.96 HV (at 25 Hz); Wear rate**:** 1.01×10^{-5} (Al_2O_3 ball); TiC conc: 91.60%.	[10]
Salt bath carburiz	Ti6Al4V alloy	640 °C; 3.5 hours; Pre-heat: 500 °C (45 min); Urea + Carbonate bath.	Depth**:** ~40 µm; Peak Hardness**:** 953.28 HV; CoF**:** 0.15	[4]

ing			(under 300 N load); Wear loss: 29x reduction.	
CVD Titanizing	VK8 & T15K6 hard alloys	1050 °C; 2–3 hours; Reduced pressure; CCl_4 chemical activator.	Thickness**:** 4.0–5.0 µm; Microhardness**:** 33.0 GPa (VK8) to 34.0 GPa (T15K6).	[11]
Gas carburizing	AISI 1020 steel	Stage 1: 950 °C, 15h, 200–300 Pa (CH_4); Stage 2: 900 °C, 3h (Salt bath).	Thickness**:** 7.5 ± 0.3 µm; Avg Microhardness**:** 1885 ± 121 HV0.025; CoF**:** 0.49; Adhesion**:** ~52 N.	[12]

Discussion

Based on analysis we can observe that there is still research work around TiC coatings, especially when it is combined as composite with other materials to use the best of two worlds, when substrate and coating improves each other. Each technique has its pros and cons, Laser cladding and TIG looks easy for scaling for industrial usage but laser cladding requires special equipment and cannot cover out of sight surfaces, same for TIG welding. ISDM requires some postprocessing to remove unnecessary cast iron layer, otherwise TiC will be sandwiched between CI layers and will have limited application. Conversely, methodologies such as chemical vapor deposition and thermal diffusion methods offer excellent conformality, enabling deposition on complex geometries and internal surfaces, albeit often requiring higher processing temperatures[3]. For example, chemical deposition and diffusion boron and titanium methods can yield reinforced layers up to 400–500 µm thick with microhardness values reaching 20,000 MPa for TiC [14]. That novel combination of chemical pretreatment and subsequent thermochemical treatment presents the possibility of achieving composite TiC coating, but the chemical pre treatment stage requires to conduct additional experimental research to develop best recipe and process parameters.

Conclusion

The advancement of hard coatings, particularly those incorporating titanium carbide, is crucial for enhancing the service life and reducing maintenance costs of components exposed to harsh environments, thereby directly addressing limitations such as low hardness and poor wear resistance [7]. This comprehensive review highlights the diverse application methods and sophisticated techniques employed for TiC surface engineering, demonstrating significant improvements in microhardness, wear resistance, and friction reduction across various substrates[3]. All analyzed recent researches of TiC coating was synthesized into a summary table 1 to highlight most important data.

References

[1] D. Ni *et al.* , "Advances in ultra-high temperature ceramics, composites, and coatings," *Journal of Advanced Ceramics* , vol. 11, no. 1, pp. 1–56, Dec. 2021, doi: 10.1007/s40145-021-0550-6.

[2] M. Mhadhbi, "Titanium Carbide: Synthesis, Properties and Applications," *Brilliant Engineering* , vol. 2, no. 2, pp. 1–11, Aug. 2020, doi: 10.36937/ben.2021.002.001.

[3] S. Kavishwar, V. Bhaiswar, S. Kochhar, A. Fande, and V. Tandon, "State-of-the-Art titanium carbide hard coatings: a comprehensive review of mechanical and tribological behaviour," *Engineering Research Express* , vol. 6, no. 4, pp. 42401–42401, Sep. 2024, doi: 10.1088/2631-8695/ad7fb7.

[4] G. Rasool, S. Mridha, and M. M. Stack, "Mapping wear mechanisms of TiC/Ti composite coatings," *Wear* , pp. 498–508, Apr. 2015, doi: 10.1016/j.wear.2015.03.022.

[5] X. Liu, L. Liu, B. Sun, B. Li, and X. Ke, "The preparation of titanium carbide thin film of Ti6Al4V at low temperature and study of friction and wear

properties," *Journal of Measurements in Engineering* , vol. 4, no. 3, pp. 167–172, Sep. 2016, doi: 10.21595/jme.2016.17563.

[6] W. Ding, Y. Yu, X. Wang, and D. Mo, "Fabrication of TiC–Fe-Based Composite Coating on 65Mn Steel Surface by Laser Cladding Technology," *Journal of Materials Engineering and Performance* , vol. 35, no. 14, pp. 14018–14030, Nov. 2025, doi: 10.1007/s11665-025-12604-5.

[7] H. Bai, L. Kang, Z. Wang, L. Zhong, and Y. Xu, "TiC–Fe gradient coating on pure titanium fabricated by in-situ solid-phase diffusion: toward superior hardness and interfacial adhesion strength," *Journal of Materials Research and Technology* , vol. 25, pp. 1141–1149, Jun. 2023, doi: 10.1016/j.jmrt.2023.06.013.

[8] D. Zhongyu, Zhangfaguang, Guoyinglu, and Chenshaobo, "TiC nano-coating and their tribological properties were deposited by doal-ion beam sputtering on the tool surface," *Journal of Physics Conference Series* , vol. 1748, no. 6, pp. 62029–62029, Jan. 2021, doi: 10.1088/1742-6596/1748/6/062029.

[9] Yu. G. Chabak *et al.* , "Structural and Tribological Studies of '(TiC + WC)/Hardened Steel' PMMC Coating Deposited by Air Pulsed Plasma," *Metals* , vol. 12, no. 2, pp. 218–218, Jan. 2022, doi: 10.3390/met12020218.

[10] R. Sharma *et al.* , "Development, Characterization, and Cavitation Erosion Analysis of High Velocity Oxy-Fuel (HVOF) sprayed TiC and (70Cu-30Ni)-Cr Based Composite Coatings on SS316 Steel," *Research Square* , May 2023, doi: 10.21203/rs.3.rs-2860707/v1.

[11] A. Q. Shamsuri *et al.* , "Effect of TiC Nanoparticles Deposition on UNS S31803 Surface Using Tungsten Arc Melting Method," *International Journal of Nanoelectronics and Materials (IJNeaM)* , vol. 18, pp. 75–83, Dec. 2025, doi: 10.58915/ijneam.v18idecember.2811.

[12] A. Dehula, N. F. Kharchenko, T. Hovorun, V. Sitnikov, V. Hryb, and D. Pakhnenko, "Structure and Properties of Diffusion Titanium Coatings Based on

Hard Alloys," *Journal of Nano- and Electronic Physics* , vol. 17, no. 6, pp. 6008–1, Jan. 2025, doi: 10.21272/jnep.17(6).06008.

[13] J. Zhang *et al.* , "Anti-wear titanium carbide coating on low-carbon steel by thermo-reactive diffusion," *Surface and Coatings Technology* , vol. 364, pp. 265–272, Feb. 2019, doi: 10.1016/j.surfcoat.2019.02.085.

[14] A. E. Stetsko and V. Korendiy, "Complex Method of Ni-Co-P Chemical Deposition and Chemical-Thermal Treatment of Boron and Titanium," in *Springer proceedings in physics* , Springer Nature, 2024, pp. 275–285. doi: 10.1007/978-3-031-67519-5_19.