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Research article

Materials Science

ULTRA-LOW FRICTION AND CORROSION PROTECTION EFFICIENCY OF TISIN/DLC HYBRID COATINGS ON TUNGSTEN CARBIDE CUTTING TOOLS

碳化鎢切削刀具上泰信/類鑽石碳混合塗層的超低摩擦和防腐效率

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Abstract

This paper aims to present the fabrication and characterization of novel TiSiN/DLC hybrid coatings for tungsten carbide cutting tools. The coatings were systematically evaluated for structural, mechanical, tribological, and corrosion resistance. The resultant TiSiN coatings, identified as superhard coatings, showed outstanding mechanical strength with a hardness of 40.9 GPa, an elastic modulus of 362 GPa, and a critical load to the coating failure (Lc) of 80 mN. The TiSiN/DLC hybrid coatings, altered to enhance properties beyond DLC coatings, demonstrated improvements, boasting a heightened hardness of 36.2 GPa with an elastic modulus of 320 GPa and an Lc of 56 mN. Tribometer tests revealed exceptional wear resistance with the lowest wear rate of 3.5×10^{-7} mm³/N·m and an ultra-low friction coefficient of 0.0274, surpassing individual TiSiN and DLC coatings. Potentiostat tests demonstrated excellent corrosion protection, with the TiSiN/DLC hybrid coatings exhibiting higher corrosion potential and lower corrosion current, culminating in an impressive corrosion protective efficiency of 97.5%. These findings highlight the multifunctional capabilities of TiSiN/DLC hybrid coatings, positioning them as promising candidates for enhancing the performance and longevity of cutting tools in diverse industrial applications.

Keywords: Titanium Silicon Nitride Coatings, Diamond-Like Carbon Coatings, Tungsten Carbide, Ultra-Low Friction, Corrosion

摘要 本文旨在介紹用於碳化鎢切削刀具的新型氮化钛/類鑽石碳混合塗層的製造和表徵。對塗層的結構、機械、摩擦學和耐腐蝕性進行了系統評估。所得氮化钛塗層被認定為超硬塗層，具有出色的機械強度，硬度為40.9 GPa，彈性模量為362

GPa，塗層失效臨界載荷為80毫牛。氮化鈦/類鑽石碳混合塗層經過修改以增強類鑽石碳塗層之外的性能，顯示出改進，硬度提高到36.2 GPa，彈性模量為320 GPa，塗層失效為56毫牛。摩擦試驗機測試顯示出卓越的耐磨性，最低磨損率為3.5×10^7毫米3/牛·米，超低摩擦係數為0.0274，超越了單獨的氮化鈦和類鑽石碳塗層。恆電位儀測試表明，氮化鈦/類鑽石碳混合塗層具有出色的腐蝕防護性能，具有更高的腐蝕電位和更低的腐蝕電流，最終達到令人印象深刻的97.5%的腐蝕防護效率。這些發現凸顯了氮化鈦/類鑽石碳混合塗層的多功能能力，使它們成為提高各種工業應用中切削刀具的性能和壽命的有前途的候選材料。

关键词: 氮化钛硅涂层、类金刚石碳涂层、碳化钨、超低摩擦、耐腐蚀

I. Introduction

Currently, in the realm of advanced materials and surface engineering, the pursuit of optimal performance for cutting tools has led to the development of innovative coating technologies, such as multilayer [1]-[3] and hybrid coatings [4]-[6]. Among these, the integration of titanium silicon nitride (TiSiN) and diamond-like carbon (DLC) hybrid coatings has emerged as a promising avenue for enhancing the frictional characteristics and corrosion resistance of tungsten carbide cutting tools. Tungsten carbide (WC), renowned for its hardness and wear resistance, forms the backbone of numerous cutting tools pivotal in machining and manufacturing processes [7]-[9]. However, challenges arise as these tools interact with diverse workpiece materials and operate under varying environmental conditions. The hybrid of both TiSiN and DLC coatings presents a multifaceted solution that mitigates frictional losses and concurrently shields the substrate material from corrosive influences.

Titanium silicon nitride (TiSiN) coatings contain titanium (Ti), silicon (Si), and nitrogen (N), corresponding to a formidable advancement in materials engineering. The incorporation of silicon elevates the coating's hardness and wear resistance, defining its exceptional properties. Renowned for their high hardness, TiSiN coatings effectively combat abrasive wear, making them indispensable for cutting tools and applications exposed to challenging conditions. Beyond their robustness, these coatings exhibit excellent wear resistance, contributing to prolonged tool life in the cutting tool industry. With applications spanning milling, drilling, and turning, TiSiN coatings demonstrate versatility in various machining operations. Their commendable performance in high-temperature environments is noteworthy due to their excellent thermal stability. The benefits of TiSiN coatings extend to enhanced wear resistance, heightened hardness compared to traditional coatings, and suitability for high-speed and dry machining environments, collectively positioning them as pivotal contributors to the efficiency and longevity of cutting tools in diverse industrial settings [10]-[12].

Diamond-like carbon (DLC) coatings characterized by amorphous carbon films that mirror the properties of natural diamonds epitomize a cutting-edge facet of material engineering. Exhibiting remarkable hardness as natural diamonds, DLC coatings offer an unprecedented solution for industries where frictional efficiency is paramount. With an intrinsic capacity for ultra-low friction, these coatings reduce heat generation during sliding or rolling contact. Furthermore, their chemical inertness shields against corrosion and chemical reactions, rendering them ideal for applications demanding robust protection. The biocompatibility of DLC coatings extends their utility to the medical realm, where they find application in implants and surgical tools. Widely adopted in the automotive sector for components such as engine parts and gears, DLC coatings contribute to friction reduction and enhanced wear resistance. The benefits of DLC coatings, including exceptional hardness without diamond brittleness, low friction properties, and corrosion resistance, position them as versatile assets across diverse industries, particularly in cutting tools where performance demands low friction and high wear resistance [13]-[15].

Both TiSiN and DLC coatings contribute significantly to the advancement of materials and surface engineering, playing key roles in enhancing the performance and longevity of tools and components in diverse applications.

The significance of this study lies in the potential enhancement of tungsten carbide cutting tools through the application of TiSiN/DLC hybrid coatings. The promising improvements in hardness, mechanical strength, wear resistance, and ultra-low friction coefficient suggest that these hybrid coatings could significantly prolong the lifespan and efficiency of cutting tools in various industrial applications. The excellent corrosion protection offered by the coatings further expands their applicability, making them valuable assets for industries where cutting tools are exposed to challenging environments. The benefits of these novel coatings could result in reduced tool replacement frequency, minimized downtime, and improved cost-effectiveness in manufacturing processes.

II. METHODOLOGY

A. Substrate Material and Preparation

The substrate material used in this study was tungsten carbide (WC), which is widely used in cutting tool production and various industrial applications. In particular, a commercial-grade RSK15X tungsten carbide substrate measuring 1.2 × 1.2 × 0.3 cm was selected for this research. The chemical composition, as determined by energy-dispersive X-ray spectroscopy (EDS) , is as follows: W (tungsten) 78.8 wt%, C (carbon) 7.8 wt%, Co (cobalt) 11.1 wt%, Si (silicon) 1.7 wt%, and Cr (chromium) 0.6 wt%. The substrates were thoroughly ground and polished for uniformity and cleanliness. Before entering the deposition chamber, ultrasonic cleaning with acetone and ethanol was performed to eliminate contaminants.

B. Coatings Deposition Process

All coatings were deposited using a filtered cathodic arc system supplied by Diacoat Technologies Company to fabricate the TiSiN, DLC, and hybrid TiSiN/DLC coatings, as shown in Figure 1.

(a) TiSiN (b) DLC (c) TiSiN/DLC

Figure 1. TiSiN, DLC, and TiSiN/DLC coatings on tungsten carbide (Developed by the authors)

1) TiSiN Coatings Deposition

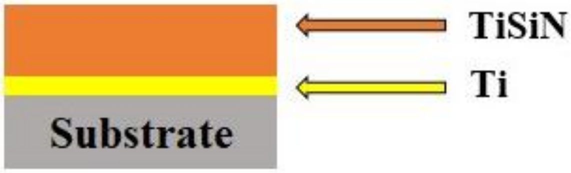
TiSiN coatings were deposited on WC-Co substrates using a multi-cathodic arc system. The deposition targets included pure titanium (99.95% purity) and a TiSi alloy (80% titanium, 20% silicon) with a 10-cm diameter. The substrate coating temperature was maintained at 480°C. The deposition process started with a 5 min deposition of pure titanium using a substrate bias voltage of 200 V and a Ti cathode current ranging from 120 to 140 A. Subsequently, the top TiSiN layer was deposited over 90 min. The TiSi cathode arc current varied from 120 to 140 A, and the bias voltage ranged from 8 to 130 A. To ensure homogenous coatings, the substrate was continuously rotated at a constant speed of 20 revolutions per minute (rpm) throughout all deposition steps.

2) Diamond-Like Carbon (DLC) Coating Deposition

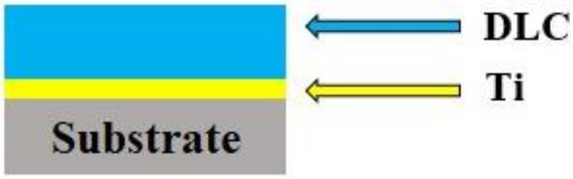
For DLC coatings, a titanium (Ti) interlayer was initially sputtered onto the substrate using DC magnetron sputtering as a glue layer. The substrate temperature was set at 170 °C, and the distance between the substrate and the Ti target was maintained at 80 mm. The vacuum chamber was evacuated to a base pressure of 3.0 x 10^{-3} Pa, followed by a 20-min argon ion etching process to eliminate possible contaminations. During DLC deposition, the cathodes operated with a DC arc current ranging from 60 to 100 A. The DC bias voltages were applied in the range from 1500 to 1700 V. The deposition time for the DLC coatings was 200 min.

3) TiSiN/DLC Coatings Deposition

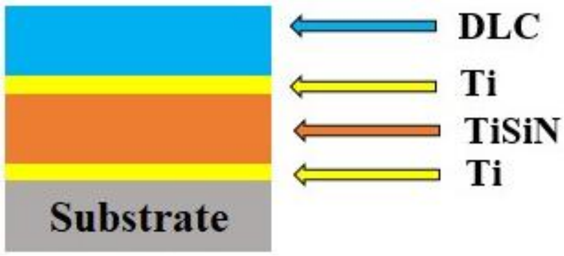
For the TiSiN/DLC hybrid coatings, a titanium (Ti) interlayer was deposited first, followed by the TiSiN and DLC layers. Figure 2 illustrates schematics of these coatings.



(a) TiSiN coatings



(b) DLC coatings



(c) TiSiN/DLC coatings

Figure 2. Schematic of the TiSiN, DLC, and TiSiN/DLC coatings (Developed by the authors)

A flowchart defining the characterization process for the coatings is presented in Figure 3. The characterization process involved coating TiSiN, DLC, and TiSiN/DLC on WC specimens and assessing the structural, mechanical, tribological, and corrosion resistance properties using appropriate testing apparatus.

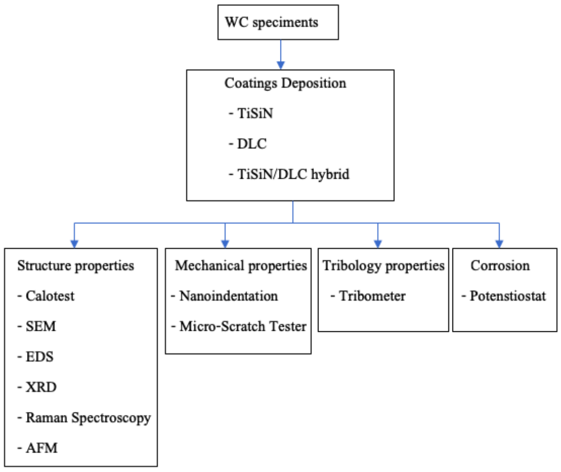


Figure 3. Flow chart of coating characterization (Developed by the authors)

III. Results and Discussion

A. Structural and Mechnical Properties

In this study, TiSiN coatings, DLC coatings, and TiSiN/DLC hybrid coatings were fabricated. The mechanical properties summarized in Table 1 reveal intriguing insights into the performance of these coatings. Building upon our previous work [1], the calotest measurements indicated that DLC coatings are notably thinner, with a thickness of approximately 1 µm, compared to TiSiN and TiSiN/DLC coatings. AFM analysis further demonstrated that DLC coatings exhibit a smaller and smoother surface roughness than the other coatings, whereas TiSiN/DLC coatings displayed the ability to reduce surface roughness compared to TiSiN coatings.

XRD analysis revealed a (111) hexagonal orientation across all coatings, indicating superior hardness. TiSiN and TiSiN/DLC coatings demonstrated a (200) preferential orientation, reinforcing their classification as superhard coatings. Nanoindentation tests revealed that TiSiN coatings, labeled superhard coatings, displayed the highest hardness at 40.9 GPa and an elastic modulus of 362 GPa. Impressively, the TiSiN/DLC hybrid coatings exhibited an enhancement in hardness, reaching 36.2 GPa and a corresponding increase in the elastic modulus to 320 GPa, surpassing the performance of DLC coatings.

Conducting micro-scratch tests further elucidated the mechanical robustness of the coatings. The TiSiN coatings demonstrated a maximum critical load (Lc) of 80 mN, demonstrating their resilience. Remarkably, the TiSiN/DLC hybrid coatings exhibited an improvement, with an increased Lc of up to 56 mN compared with the DLC coatings. These findings underscore the potential of TiSiN/DLC hybrid coatings to augment mechanical properties, presenting a compelling avenue for enhancing coating performance in real-world applications.

Table 1.
Thickness, roughness, and mechanical properties of the resultant coatings (Developed by the authors)

Coatings material	Coating thickness (µm)	Roughness RMS (nm)	Coating texture	Hardness (GPa)	Elastic modulus (GPa)	Critical load (mN)
TiSiN	1.56	46.07	(111), (110), (200)	40.9	362	80
DLC	1.03	9.97	(111), (110)	36.0	333	41
TiSiN/DLC	1.77	36.74	(111), (110), (200)	36.2	320	56

B. Tribological Examination by a Tribometer Test

The key of this study is to explore the tribological properties of the resultant coatings, focusing on wear and friction in particular. The tribometer tests, conducted using an Al_2O_3 ball with a 10 N load, yielded valuable data summarized in Table 2. Notably, the TiSiN/DLC hybrid coating exhibited outstanding wear resistance, manifesting the lowest wear rate recorded at 3.5×10^{-7} mm^3/Nm. In contrast, the DLC and TiSiN coatings, as illustrated in Figure 4, displayed comparatively higher wear rates. The wear rate was calculated based on the following equation:

$$W = \frac{V}{(F \times d)} \quad (1)$$

where V is the wear volume from the tribometer test, F is the applied normal load (10 N), d is the sliding distance (200 m), and W is the wear rate with the unit mm^3/N·m [3].

Table 2.
Tribolical properties of the resulting coatings (Developed by the authors)

Coatings	Wear rate ($x10^{-7} mm^3$/N.m)	Coefficient of friction (COF)
TiSiN	21	0.1918
DLC	4.5	0.0632
TiSiN/DLC	3.5	0.0274

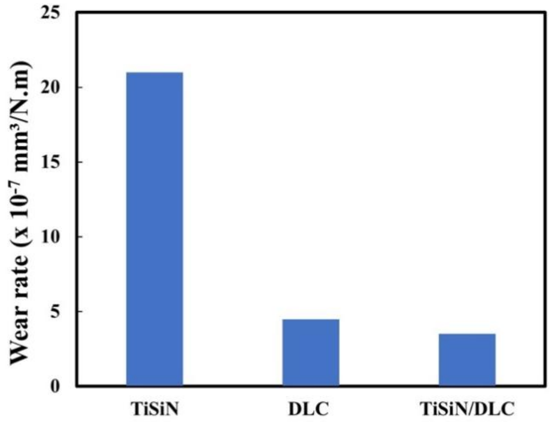


Figure 4. Wear rate of the resulting coatings (Developed by the authors)

Investigating the coefficient of friction (COF), the TiSiN/DLC hybrid coatings emerged as a standout performer, showcasing an ultra-low friction coefficient of 0.0274. This represents a substantial reduction in friction compared with the DLC and TiSiN coatings, as demonstrated in Figure 5.

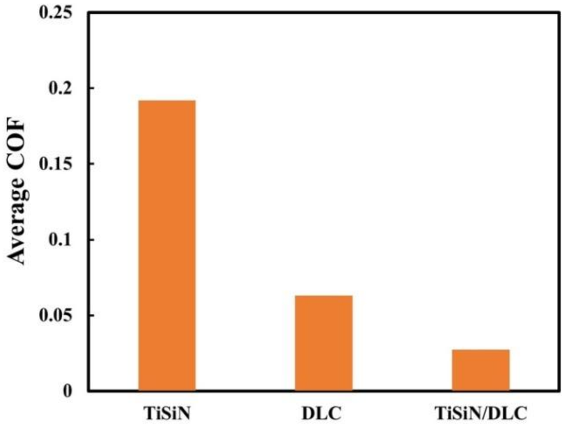


Figure 5. Average coefficient of friction of the resulting coatings (Developed by the authors)

The data highlight the effectiveness of the TiSiN/DLC hybrid coating in simultaneously achieving excellent wear resistance and ultra-low friction, which are crucial attributes for applications in which minimizing wear and frictional forces is paramount. These promising results position the TiSiN/DLC hybrid coating as an impressive candidate for advancing the performance and longevity of cutting tools in practical industrial settings.

C. Potenstiostat Test

This segment of the study examines the corrosion resistance of the coatings, primarily investigated through potentiostat tests in a 3 wt% NaCl solution. The resulting polarization curve, as depicted in Figure 6, provides insights into the corrosion behavior of the coatings. Table 3 shows the corrosion data, revealing the exemplary corrosion resistance of the TiSiN/DLC hybrid coating.

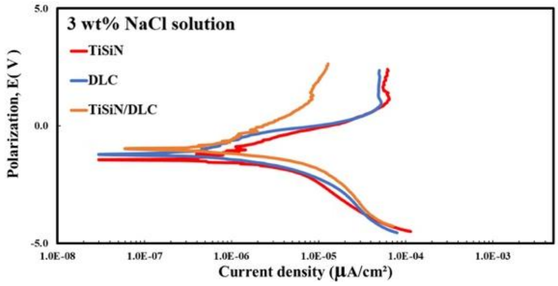


Figure 6. Polarization curve of the resulting coatings (Developed by the authors)

Table 3.
Corrosion resistance of the resulting coatings (Developed by the authors)

Coatings	E_{corr} (V)	i_{corr} ($\mu A/cm^2$)	% P_e
TiSiN	-0.398	2.29	92.6
DLC	-0.283	0.955	96.9
TiSiN/DLC	-0.261	0.766	97.5
WC uncoated	-0.847	30.94	Ref.

The potentiostat test emphasized the exceptional corrosion resistance of the TiSiN/DLC hybrid coating, as evidenced by a higher E_{corr} = -0.261 V and the lowest i_{corr} = 0.766 $\mu A/cm^2$ compared with the DLC and TiSiN coatings. Figure 7 further emphasizes the superiority of TiSiN/DLC coatings by demonstrating that the corrosion protective efficiency (%P_e) of coatings can be determined by the following equation:

$$P_e(\%) = \left[\left(1 - \frac{i_{corr}}{i_{corr}^{WC}}\right)\right] \quad (2)$$

where I_{corr} and I_{corr}^{WC} represent the corrosion current densities of the coatings and uncoated WC, respectively. TiSiN/DLC coatings exhibited the highest % of P_e at 97.5% compared with uncoated WC.

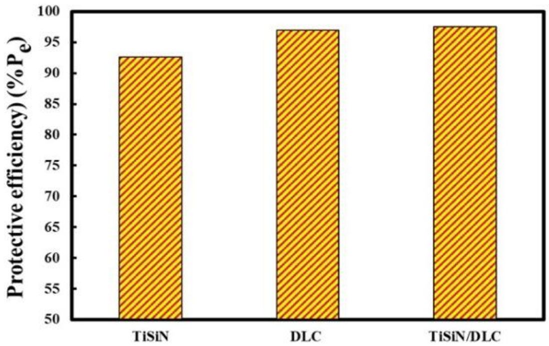


Figure 7. Percentage of protective efficacy of the resultant coatings (Developed by the authors)

The achievement of our novel results lies in the comprehensive evaluation and characterization of TiSiN/DLC hybrid coatings, particularly for customization of tungsten carbide cutting tools. This work not only establishes the outstanding mechanical and tribological properties of the hybrid coatings but also proves their superiority over individual TiSiN and DLC coatings. The designed hybrid coatings demonstrate a unique combination of enhanced hardness, mechanical strength, wear resistance, and ultra-low friction coefficient. Furthermore, this study focuses on the corrosion resistance properties of these coatings, showcasing their superior performance in protecting against corrosion. This holistic exploration contributes potential insights to the field of coating technology and material science, presenting a novel and effective solution for improving the durability and functionality of cutting tools.

IV. CONCLUSION

On the basis of the experiment, this paper studies the fabrication and development of novel TiSiN/DLC hybrid coatings, investigating their structural, mechanical, tribological, and corrosion resistance properties on tungsten carbide cutting tools. The results of this study are summarized as follows.

(1) TiSiN coatings, which are recognized as superhard coatings, demonstrate outstanding mechanical properties with a hardness of 40.9 GPa and an elastic modulus of 362 GPa. These coatings also exhibit a high critical load (Lc) of 80 mN, indicating substantial mechanical resilience. In comparison, TiSiN/DLC hybrid coatings, designed to enhance mechanical characteristics beyond those of DLC coatings, display notable improvements. The hybrid coatings achieve a heightened hardness of 36.2 GPa and an elastic modulus of 320 GPa while maintaining a critical load (Lc) of 56 mN.

(2) For tribological tests, the TiSiN/DLC hybrid coatings showed exceptional wear resistance, boasting the lowest wear rate of 3.5×10^{-7} $mm^3/N{\cdot}m$ and an ultra-low friction coefficient of 0.0274. These values surpass those of individual TiSiN and DLC coatings, underscoring the synergistic benefits of the hybrid approach in achieving superior tribological performance.

(3) Potentiostat tests provide valuable insights into the corrosion resistance of the coatings. TiSiN/DLC hybrid coatings demonstrate remarkable corrosion protection, exemplified by a higher corrosion potential (E_{corr}) of -0.261 V, a lower corrosion current (i_{corr}) of 0.766 $\mu A/cm^2$, and an impressive corrosion protective efficiency (% of P_e) of 97.5%. These findings position TiSiN/DLC hybrid coatings as a versatile solution with multifunctional capabilities that address critical aspects of mechanical strength, wear resistance, low friction, and corrosion protection.

For limitations of the study perspectives despite the promising results, it is essential to acknowledge certain limitations in this paper. The current research primarily focuses on laboratory-scale evaluations, and further real-industrial-scale testing under diverse operational conditions examines the coatings' performance in practical industrial applications. In addition, long-term durability and stability need to be assessed to ensure sustained effectiveness over extended usage periods. Future research avenues could involve optimizing the coating thickness, exploring variations in composition, and investigating the scalability of the fabrication process to facilitate industrial-scale implementation. Collaborative efforts with industry partners can provide valuable insights into specific application requirements and further refine coatings for customized industrial needs.

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