

The Development of Advanced Coating Technologies for Cutting Tools for Difficult-to-machine Materials

Longyu Xiong

School of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin, China

ABSTRACT

With the rapid advancement of modern manufacturing toward high efficiency, precision, and sustainability, the extensive application of difficult-to-machine materials such as titanium alloys and carbon fiber reinforced composites in aerospace and other high-tech fields has imposed increasingly stringent demands on cutting tool performance. Coated tool technology, which involves depositing micro- to nano-scale functional thin films onto tool substrates, has emerged as a critical approach to enhance wear resistance, high-temperature durability, and service life of cutting tools. This paper focuses on Physical Vapor Deposition (PVD) technologies, particularly arc ion plating, for tool coating fabrication. It systematically reviews recent research progress in transition metal nitride coatings as well as nanomultilayer coatings. Studies indicate that through compositional optimization and multilayer structural design, coatings can achieve a synergistic improvement in hardness, toughness, thermal stability, and oxidation resistance. These enhancements effectively reduce cutting friction and temperature, inhibit tool wear, and significantly improve performance and longevity in machining difficult-to-cut materials. Coating technology is evolving toward composite, nanostructured, and functionally graded designs, providing essential technical support to address future challenges in efficient and sustainable manufacturing.

KEYWORDS

Tool Coating Technology; Physical Vapor Deposition; Difficult-to-machine Materials.

1. INTRODUCTION

With the vigorous development of modern manufacturing, difficult-to-machine materials such as carbon fiber reinforced composites and titanium alloys are increasingly used in aerospace and other fields. Their processing methods are rapidly evolving towards high efficiency, continuity, and environmental sustainability. Under this trend, adopting green and clean cutting processes has emerged as a core direction for the future development of the manufacturing industry [1]. The widespread application of difficult-to-machine materials and the deepening advancement of green manufacturing concepts have imposed higher requirements on the wear resistance and high-temperature performance of cutting tools. When machining high-specific-strength or new difficult-to-machine materials, the use of conventional cemented carbide tools often leads to rapid tool wear, thereby affecting tool life and part machining accuracy. To address this, depositing one or multiple layers of high-wear-resistant refractory metal or metallic compound coatings on the tool substrate has become an effective approach to enhance tool performance and extend its service life [2].

Titanium alloys possess excellent characteristics such as high specific strength, corrosion resistance, and high-temperature durability, demonstrating broad application prospects in aerospace, defense and military industries, biomedical fields, and more. However, titanium alloys are also typical difficult-to-machine materials. Their poor thermal conductivity, high chemical activity, and low elastic

modulus make them challenging in cutting processes, posing severe demands on tool performance. During cutting, heat generated is not easily dissipated through chips or the workpiece, leading to elevated temperatures in the cutting zone and at the tool edge. At high temperatures, titanium tends to adhere to the tool material, while titanium alloys are prone to react with elements such as oxygen and nitrogen, forming a hard and brittle layer on the machined surface that accelerates tool wear. Furthermore, the low elastic modulus of titanium alloys causes elastic recovery of the machined surface, increasing contact stress and friction between the flank face and the workpiece, thereby further exacerbating tool wear. Therefore, to meet the demands of efficient titanium alloy machining, it is essential to enhance the mechanical and tribological properties of coated tools under high-speed and high-temperature conditions, reduce friction between the tool and workpiece, and suppress heat accumulation during cutting, thereby extending tool life and improving machining efficiency and quality [3].

Carbon fiber reinforced composites exhibit high specific strength and specific modulus, good fatigue resistance, corrosion resistance, and strong design flexibility, making them widely used in aerospace, wind power, automotive, and other fields. However, during milling, their high hardness tends to cause rapid tool wear. Simultaneously, due to the anisotropic nature of the material, significant differences in mechanical properties across different directions can easily lead to machining defects such as burrs and flashes on the workpiece surface, severely affecting surface quality and machining efficiency. Coating the tool surface with a high-hardness, low-friction coating can effectively reduce cutting resistance, minimize fiber tearing and pull-out phenomena, and suppress deformation and delamination during workpiece processing, thereby enhancing tool durability and ensuring machining quality [4].

To address the aforementioned challenges, coated tool technology has emerged and become one of the core supporting technologies in modern advanced manufacturing. Coated tools are engineered by precisely depositing one or multiple layers of functional thin films—ranging from micrometers to nanometers in thickness—onto the tool substrate, thereby endowing the tools with comprehensive properties that surpass the intrinsic limitations of their base materials [5]. These coatings typically consist of high-hardness compounds such as nitrides, carbides, oxides, or their composite systems, exhibiting excellent high-temperature resistance, superior wear resistance, strong chemical stability, and good thermal shock resistance.

The presence of coatings not only significantly enhances the tool surface's resistance to abrasive and diffusion wear but also maintains high hardness at elevated temperatures, effectively delaying tool softening. Meanwhile, well-designed coating surfaces can substantially reduce the friction coefficient during cutting, decreasing cutting forces and heat generation, thereby suppressing built-up edge formation and lowering cutting temperatures [6]. This synergy of effects collectively extends tool service life manifold and markedly improves workpiece surface quality, dimensional accuracy, and geometric tolerances.

With the expanding application of difficult-to-machine materials such as titanium alloys, high-temperature alloys, and high-strength steels in aerospace, new energy, precision mold, and other advanced fields, traditional single-layer coatings can no longer meet the comprehensive performance demands under extreme working conditions. Consequently, current research has shifted toward designing and developing high-performance composite coating systems to address next-generation machining challenges. These coatings aim to achieve synergistic optimization of multiple properties, including ultra-high hardness, high thermal stability, high toughness, low friction, and anti-adhesion [7]. Through advanced structural designs such as nanomultilayers, functionally graded architectures, multicomponent composites, and superlattices, coated tools are evolving toward intelligent and customized solutions, poised to provide critical tool technology support for efficient, precise, and sustainable future manufacturing.

Soft coatings with self-lubricating properties can significantly reduce material adhesion and friction during dry cutting, effectively delaying tool wear and lowering cutting temperatures, thus extending tool service life [8]. However, soft coatings generally suffer from low hardness and insufficient wear resistance. If only a single soft coating is applied on the tool surface, the coating tends to fail too quickly, making it difficult to continuously protect the tool substrate. Therefore, developing high-performance self-lubricating coatings that combine excellent mechanical properties with good lubrication characteristics has become a forefront research hotspot in the fields of high-speed cutting and coated tools.

2. THE PREPARATION METHOD OF THE HARD COATING

The preparation of tool coatings typically employs vapor deposition technology. In a vacuum environment, this method utilizes physical or chemical changes in the vapor phase substances to deposit a high-hardness thin film on the surface of the tool substrate, thereby effectively enhancing the tool's wear resistance and cutting performance.

2.1. Physical Vapor Deposition Technology

Physical Vapor Deposition (PVD) is a widely adopted modern thin-film fabrication technique in contemporary industry, particularly suitable for depositing high-performance and functional coatings on various material surfaces. Its fundamental principle can be summarized as follows: Under vacuum or low-pressure conditions, external energy sources—such as thermal energy, kinetic energy, or plasma energy—are employed to physically convert solid or liquid target materials into gaseous atoms, molecules, or ions via methods such as sputtering, evaporation, or glow discharge. These vapor-phase particles subsequently migrate within the vacuum chamber and ultimately reach and deposit onto the pretreated substrate surface [9]. During the deposition process, the vapor-phase particles undergo a series of complex dynamic stages on the substrate surface, including initial adsorption, surface diffusion, nucleation and growth of critical nuclei, culminating in the formation of a uniform, dense coating with a specific microstructure through island growth, layer-by-layer growth, or hybrid growth modes.

This technology encompasses a variety of specific processes, such as magnetron sputtering, arc ion plating, electron beam evaporation, and pulsed laser deposition, allowing for flexible selection and optimization of process parameters according to different application requirements. The key characteristics of PVD technology include high deposition efficiency, relatively low process temperatures (making it suitable for thermally sensitive materials), low overall energy consumption, and significant environmental benefits, as the entire physical process typically takes place in an enclosed vacuum environment without the use or generation of hazardous chemical substances. Simultaneously, PVD coatings are highly favored for their outstanding comprehensive properties: the deposited coatings exhibit excellent chemical stability, strong oxidation and corrosion resistance, dense microstructure with minimal defects, and robust adhesion to the substrate. These coatings generally possess high hardness and exceptional wear resistance, significantly extending the service life of tools, molds, and critical components. Moreover, by adjusting process parameters and target material composition, precise control over coating thickness, composition, structure, as well as optical, electrical, and decorative properties can be achieved. Consequently, PVD technology plays an indispensable role in various high-tech fields, including mechanical manufacturing, aerospace, electronic information, medical devices, and high-end decorative applications.

Based on the evaporation methods of metal ions, PVD technology can be primarily classified into two categories: vacuum evaporation coating and ion sputtering coating.

Vacuum evaporation coating involves heating the coating material within a vacuum chamber to vaporize it, forming a directional vapor flux. This vapor subsequently deposits and condenses onto

the substrate surface to form a solid thin film. This process typically requires high-vacuum conditions to minimize collisions and chemical reactions between evaporated atoms and residual gas molecules, thereby ensuring high-density and high-purity coatings. Additionally, this technique demands raw materials with high melting points and low vapor pressures. While vacuum evaporation offers simplicity in process and relatively high deposition rates, its limited heating temperature and low kinetic energy of evaporated particles result in insufficient adhesion between the film and the substrate, which restricts its application range to some extent.

The fundamental process of ion sputtering coating involves the bombardment of a target material by Ar^+ ions, accelerated by an electric field within a plasma generated by glow discharge in an inert gas (such as argon). This bombardment causes target atoms to be ejected and migrate to the substrate surface, where they ultimately deposit to form a dense thin film. Among ion sputtering techniques, magnetron sputtering is the most widely used [10]. This method employs a magnetic field applied perpendicular to the electric field on the surface of the cathode target. The Lorentz force acting on electrons, combined with electric field acceleration, alters their linear trajectories into cycloidal paths. This extends the electron travel distance, increases collision probabilities with gas molecules, and significantly enhances gas ionization efficiency. However, magnetron sputtering also faces challenges such as relatively low deposition rates, limited coating-substrate adhesion, and low target material utilization, which constrain its further application in fields like cutting and machining.

2.2. Arc Ion Plating Technology

Arc ion plating, with its superior throwing power and high metal target ionization rate of up to 80%, has become one of the most widely applied PVD technologies in the field of tool coatings. Coatings produced using this technique exhibit characteristics such as high density, uniformity, strong coating-substrate adhesion, and excellent mechanical properties. The core components of the system include a vacuum chamber, a substrate rotating fixture, a cathode arc source, and a bias power supply.

The technological principle is based on arc discharge: in a vacuum environment, the cathode target material evaporates and ionizes to form a high-energy plasma, and the charged particles are directionally accelerated and deposited onto the substrate surface under the influence of an electric field, ultimately forming a high-performance thin film. The plasma generated by this technique is uniformly distributed and exhibits excellent particle throwing power, making it particularly suitable for coating surfaces of complex-shaped components. By applying an external coil magnetic field, the arc spot can be made to move uniformly across the target surface, improving target material utilization. Simultaneously, adjusting the arc spot movement speed effectively refines metal particles. The ion energy can reach 40–100 eV, which helps enhance coating uniformity and coating-substrate adhesion. In practical operation, multiple targets can undergo arc discharge simultaneously, significantly increasing the deposition rate and deposition coverage, making this technology suitable for industrial-scale batch production.

However, during the arc discharge process, some vaporized particles may condense to form droplets. These droplets deposit on the coating surface or become embedded within it as large-sized particles, creating defects such as voids, which increase surface roughness and negatively affect coating performance. To address this, researchers have continuously optimized the process and proposed various improvement strategies. Among these, the synergistic regulation of arc spot motion using combined electromagnetic and permanent magnetic fields has proven effective in suppressing droplet formation, thereby improving the microstructure and surface properties of the coatings.

3. RESEARCH PROGRESS ON TOOL COATINGS

With the continuous advancement of global manufacturing towards high-end and intelligent development, cutting-edge sectors such as aerospace, new energy vehicles, and precision medical

devices have witnessed a surge in demand for high-performance components. This has led to the expanding application range of difficult-to-machine materials, including titanium alloys, high-temperature alloys, high-strength steels, and composite materials. These materials often exhibit characteristics such as high strength, high hardness, high toughness, or low thermal conductivity, posing unprecedented challenges to mechanical machining. In this context, advanced tool coating technology, as a key enabler for enhancing the overall efficiency of cutting systems, has become increasingly strategically significant [11].

By precisely depositing one or multiple layers of functional thin films, ranging from micrometers to nanometers in thickness, onto the tool substrate (typically made of cemented carbide, high-speed steel, or ceramics), the interfacial properties of the tool can be fundamentally optimized. This protective "armor" significantly enhances the macro-hardness and high-temperature hardness of the tool surface, effectively resisting abrasive and adhesive wear. Simultaneously, the low friction coefficient of the coating reduces cutting forces and heat generation, while its excellent chemical stability prevents oxidation and diffusion wear at elevated temperatures. As a result, the service life of coated tools can be extended by several to dozens of times, not only reducing per-unit machining costs but also ensuring dimensional stability and surface integrity of the workpiece, thereby significantly improving production efficiency and product yield.

In contemporary machining practices, as workpiece materials become more complex in composition and structure, and requirements for dimensional accuracy, geometric tolerances, and surface roughness reach extreme levels, the service conditions for cutting tools have become exceptionally demanding. Particularly under high-efficiency and environmentally friendly machining conditions such as dry cutting, high-speed cutting, and hard machining, the tool edge is subjected to intense mechanical stress, thermal stress, and thermal shock. When machining difficult-to-cut materials, severe friction can generate concentrated temperatures exceeding 800°C at the tool-chip interface in an extremely short period. Traditional single-material coatings (e.g., TiN) under such extreme conditions are prone to rapid oxidation, softening, and interdiffusion of elements, leading to premature coating wear, delamination, and subsequent issues such as tool chipping, workpiece surface burning, and loss of machining accuracy. Clearly, traditional tool coating systems characterized by uniform single-layer structures have reached performance limitations and can no longer meet the comprehensive demands of modern manufacturing for "high efficiency, high precision, high reliability, and long service life."

Therefore, to address future machining challenges, the development of a new generation of high-performance composite tool coatings has emerged as a core research frontier at the intersection of advanced manufacturing technology and material surface engineering. The primary objective is to overcome the inherent limitations of material properties through cross-scale structural design, achieving synergistic enhancement of multiple, often conflicting, performance metrics such as high hardness, high toughness, high thermal stability, low friction coefficient, and strong oxidation resistance.

In recent years, the design philosophy of tool coatings has undergone a revolutionary transformation, evolving from homogeneous single-layer structures to multicomponent composites, and from simple multilayer configurations to gradient/nanostructured architectures. By integrating materials with different properties (e.g., nitrides, carbides, oxides, and metals) into advanced configurations such as nanomultilayers, nanocomposites, superlattices, or functionally graded structures, the interfacial effects, coupling effects, and size effects among the components can be leveraged to achieve macroscopic performance leaps. For instance, the addition of elements like Cr, Si, or Y to AlTiN coatings forms solid-solution strengthening, enhancing thermal stability; nanomultilayer structures such as TiAlN/AlCrN can inhibit crack propagation through interfaces, combining high hardness and toughness; while the combination of DLC (diamond-like carbon) with hard ceramic coatings achieves an optimal balance of extremely low friction and high wear resistance. These diversified, systematic, and customizable advanced coating solutions are driving cutting-edge machining technologies to

continuously break through existing limits, providing essential foundational support for the ongoing advancement of the manufacturing industry.

3.1. Transition Metal Nitride Coating

Transition metal nitrides are widely used in the wear-resistant protection of cutting tools and molds due to their high hardness, excellent wear resistance, and good thermal stability. Among the various nitride coatings, TiN and CrN coatings are the most extensively applied. To further enhance performance, researchers often introduce ternary or additional elements for alloying to meet practical machining requirements. For example, Huang Shutao et al. [12] investigated the performance of TiN-coated tools in turning D60 steel. They found that under water-soluble coolant conditions, significant thermal stress between the substrate and coating led to reduced wear resistance. In contrast, under dry high-speed cutting conditions, no coating delamination occurred, wear resistance improved significantly, and the tools achieved stable long-term cutting. Chowdhury et al. [13] deposited CrN coatings on cemented carbide tools for machining Ti6Al4V alloy and observed that the Cr₂O₃ film formed during cutting acted as a lubricant, resulting in a markedly longer tool life for coated tools compared to uncoated ones.

Compared to traditional nitride coatings, AlCrN coatings exhibit higher hardness, wear resistance, and chemical stability. At high temperatures, they form dense Al and Cr oxide layers, providing excellent high-temperature oxidation resistance up to 1000°C. Currently, AlCrN coatings are primarily prepared via magnetron sputtering and arc ion plating. Magnetron sputtering produces coatings with smooth surfaces and high quality but lower deposition efficiency. In contrast, arc ion plating enables the preparation of dense AlCrN coatings with high deposition efficiency, making it more widely adopted in industrial applications. Yang Xiaopan et al. [14] prepared AlCrN coatings on cemented carbide substrates using multi-arc ion plating and conducted cutting experiments. They observed that the flank wear reached the bluntness criterion after a cutting length of 2.8 m, with the tool life being 1.27 times that of TiN-coated tools.

To further enhance performance, Si is incorporated into AlCrN to form AlCrSiN nanocomposite coatings. Si exists in the amorphous Si_xN phase, effectively inhibiting dislocation motion and crack propagation, thereby significantly improving coating hardness, thermal stability, and oxidation resistance. He Cheng [15] studied AlCrSiN coatings with varying Si content and found that as Si content increased, adhesion strength improved, while hardness first increased and then decreased, peaking at 33.4 GPa with a Si content of 5.58%. Compared to CrAlN coatings, AlCrSiN-coated tools exhibited lower cutting forces, better wear resistance, and longer service life when milling stainless steel. Liu Yanmei et al. [16] prepared AlCrSiN coatings at different deposition temperatures using arc ion plating with variable magnetic field intensity. They observed that as temperature increased, the CrN phase gradually replaced the Cr₂N phase, and coating hardness and elastic modulus rose accordingly, reaching peak values of 25.59 GPa and 501.76 GPa at 450°C. Zhong Xing et al. [17] prepared AlCrSiN coatings via pulsed and DC arc ion plating and found that coatings at different duty cycles exhibited an fcc single-phase structure, presenting a nanocomposite morphology of amorphous Si₃N₄ encapsulating nanocrystalline (Al,Cr)N. At a duty cycle of 1%, the coating surface quality and hardness (31.5 GPa) were optimal, with outstanding thermal stability: hardness remained above 30 GPa after annealing at 950°C, and the oxidation resistance temperature exceeded 1000°C. However, some studies have noted that AlCrSiN coatings exhibit a high friction coefficient and reduced wear resistance at temperatures above 500°C, limiting their application in high-temperature and high-speed cutting [18].

To improve high-temperature performance, W can be introduced into AlCrSiN. Solid solution strengthening by W and the formation of WN phases enhance hardness, while the generated WO₃ phase helps reduce the friction coefficient and improve wear resistance [19]. Fu et al. [20] prepared CrAlSiWN coatings using multi-arc ion plating and optimized process parameters through orthogonal

experiments. Results showed that the coating consisted of an fcc-(Cr,Al)N solid solution, with hardness four times that of the substrate, adhesion strength reaching 89.2 N, and a low friction coefficient of 0.478. The coating demonstrated excellent thermal stability under vacuum annealing up to 1100 °C and exhibited good oxidation resistance at 1100 °C. The study examined changes in surface morphology and composition after oxidation at 800–1250 °C: fine white particles appeared at 800 °C; during oxidation, large particles spalled, forming pits and pores that provided channels for inward oxygen diffusion; needle-like oxides formed on the surface at 1100 °C; and at 1250 °C, the morphology transitioned to a dendritic structure, primarily composed of iron oxides, indicating coating failure.

3.2. Nano Multilayer Coating

A nanomultilayer coating is a periodically structured system formed by alternately depositing nanometer-scale thin films of different compositions on a substrate surface. Its key structural parameters include the modulation period (the sum of the thicknesses of two adjacent layers) and the modulation ratio (the thickness proportion of each layer within a single period). By rationally designing the nanomultilayer structure, the advantages of different materials can be integrated to effectively enhance the coating's mechanical properties, reduce internal stress, improve coating-substrate adhesion, optimize microstructure and wear resistance, and ultimately achieve a synergistic improvement in hardness, toughness, and thermal stability [21].

Xiao et al. [22] deposited AlCrN, AlTiSiN, and nanomultilayer AlCrN/AlTiSiN coatings on cemented carbide (WC-6 wt% Co) and Al₂O₃ substrates using arc ion plating technology, systematically comparing their mechanical properties, oxidation resistance, and cutting performance. The study found that compared to single-layer AlCrN and AlTiSiN coatings, the nanomultilayer AlCrN/AlTiSiN coating exhibited a denser two-phase microstructure, with significantly improved hardness and adhesion strength. This coating demonstrated excellent oxidation resistance at 1000°C, forming a thin and dense aluminum-rich oxide layer on its surface. The multilayer structure effectively inhibited elemental diffusion and delayed the oxidation process. In turning experiments, the AlCrN/AlTiSiN coating achieved the longest service life, with a cutting length reaching approximately 800 m.

Luo et al. [23] prepared CrAlN/TiSiN nanomultilayer coatings. Transmission electron microscopy analysis revealed that the coatings exhibited a typical columnar crystal structure, consisting of alternating dark TiSiN layers and bright CrAlN layers in a periodic arrangement. Amorphous regions were observed within the TiSiN layers, indicating the presence of an amorphous SiN_x phase. Coherent/semi-coherent interfaces introduced alternating strain fields into the multilayer structure, effectively hindering dislocation motion. When the modulation period was 19 nm, the CrAlN/TiSiN coating achieved its highest hardness of 41.59 GPa.

Song et al. [24] prepared AlCrN, AlCrBN, and AlCrN/AlCrBN nanomultilayer coatings using multi-arc ion plating technology. The study showed that all three coatings were primarily composed of a face-centered cubic solid solution, fcc-(Cr,Al)N phase. Compared to the single-layer AlCrN and AlCrBN coatings, the AlCrN/AlCrBN multilayer coating exhibited superior thermal stability and oxidation resistance. When the annealing temperature reached 1000°C, significant precipitation of the w-AlN phase occurred in both AlCrN and AlCrBN coatings, while the Cr-N phase decomposed to form the h-Cr₂N phase, leading to a notable decline in hardness. In contrast, during annealing between 800–1000°C, the multilayer structure of AlCrN/AlCrBN effectively suppressed the formation of w-AlN and h-Cr₂N, maintaining stable coating hardness. Hardness only began to decrease when the temperature rose to 1200°C. During high-temperature oxidation, the multilayer structure similarly inhibited spinodal decomposition between the AlCrN and AlCrBN layers. At 1000°C, a dense oxide layer formed on the coating surface, which not only hindered the outward diffusion of Al and Cr atoms but also effectively suppressed the inward penetration of oxygen.

REFERENCES

- [1] Zhao G, Zhao B, Ding W, et al. Nontraditional energy-assisted mechanical machining of difficult-to-cut materials and components in aerospace community: a comparative analysis[J]. *International Journal of Extreme Manufacturing*, 2024, 6(2): 022007.
- [2] Bobzin K. High-performance coatings for cutting tools[J]. *CIRP Journal of Manufacturing Science and Technology*, 2017, 18: 1-9.
- [3] Ichou H, Arrousse N, Berdimurodov E, et al. Exploring the advancements in physical vapor deposition coating: a review[J]. *Journal of Bio-and Tribo-Corrosion*, 2024, 10(1): 3.
- [4] HU J, TIAN X, LIU H, et al. Enhanced discharge and microstructure of the ta-C coatings by electromagnetically enhanced cathodic arc at argon atmosphere[J]. *Surface and Coatings Technology*, 2019, 365: 227-236.
- [5] Shrivastava S, Rajak D K, Joshi T, et al. Ceramic Matrix Composites: Classifications, Manufacturing, Properties, and Applications[J]. *Ceramics*, 2024, 7(2): 652-679.
- [6] Cao J, Xia J, Shen X, et al. Research Progress on Rolling Forming of Tungsten Alloy[J]. *Materials*, 2024, 17(18): 4531.
- [7] XIAO B-J, CHEN Y, DAI W, et al. Microstructure, mechanical properties and cutting performance of AlTiN coatings prepared via arc ion plating using the arc splitting technique[J]. *Surface and Coatings Technology*, 2017, 311: 98-103.
- [8] Dang C, Lin W, Meng F, et al. Enhanced tensile ductility of tungsten microwires via high-density dislocations and reduced grain boundaries[J]. *Journal of Materials Science & Technology*, 2021, 95: 193-202.
- [9] Liu Y, Liu H D, Wan Q, et al. High-temperature oxidation behaviour of AlTiSiN and AlCrSiN coatings[J]. *Surface Engineering*, 2019, 35(8): 652-660.
- [10] Geng D, Li H, Chen Z, et al. Microstructure, oxidation behavior and tribological properties of AlCrN/Cu coatings deposited by a hybrid PVD technique[J]. *Journal of Materials Science & Technology*, 2022, 100: 150-160.
- [11] Zhu S, Qin Y, Mei H. Influence of Arc Current on Surface Properties and Corrosion Resistance of AlCrN Coatings Deposited by Multi-arc Ion Plating[J]. *International Journal of Electrochemical Science*, 2020, 15(6): 5352-5361.
- [12] Shutao Huang, Chunde Jia, Zenghui Jiang, et al. High-Speed Turning and Milling Performance and Wear Mechanism of TiN-Coated Tools[J]. *Journal of Harbin Institute of Technology*, 2008, (09): 1501-1505.
- [13] Chowdhury M S I, Bose B, Rawal S, et al. Investigation of the wear behavior of pvd coated carbide tools during Ti6Al4V machining with intensive built up edge formation[J]. *Coatings*, 2021, 11(3): 266.
- [14] Xiaopan Yang, Haiyang Lin, Yicong Chen, et al. Influence of Multi-arc Ion Plating Process on Coating Properties of Cemented Carbide PCB Milling Cutters[J]. *Diamond & Abrasives Engineering*, 2023, 43(05): 586-591.
- [15] Cheng He. Preparation and Properties of AlCrSiN Coatings[D]. Shanghai: Shanghai Institute of Technology, 2020.
- [16] Yanmei Liu, Rui Zhang, Qiang Zhu, et al. Effect of Deposition Temperature on AlCrSiN Coatings Prepared by Arc Ion Plating[J]. *Surface Technology*, 2023, 52(07): 149-157.
- [17] Xing Zhong, Qimin Wang, Yuxiang Xu, et al. Effect of Duty Cycle on Thermal Stability and Oxidation Resistance of AlCrSiN Coatings Prepared by Pulsed Arc Ion Plating[J]. *China Surface Engineering*, 2018, 31(05): 99-107.
- [18] Yau B S, Chu C W, Lin D, et al. Tungsten doped chromium nitride coatings[J]. *Thin Solid Films*, 2008, 516(8): 1877-1882.
- [19] Huang X, Xie Z, Li K, et al. Microstructure, wear and oxidation resistance of CrWN glass molding coatings synthesized by plasma enhanced magnetron sputtering[J]. *Vacuum*, 2020, 174: 109206.
- [20] Fu Y, Wang G, Zhu Y, et al. Critical processing parameters optimization and characterization of CrAlSiWN coating by industrial arc ion plating[J]. *Vacuum*, 2024, 226: 113313.
- [21] Wang D, Lin S, Liu L, et al. Micro-nano multilayer structure design and solid particle erosion resistance performance of CrAlN_x/CrAlN coating[J]. *Vacuum*, 2020, 172: 109064.
- [22] Xiao B, Zhang T F, Guo Z, et al. Mechanical, oxidation, and cutting properties of AlCrN/AlTiSiN nano-multilayer coatings[J]. *Surface and Coatings Technology*, 2022, 433: 128094.
- [23] Luo Y, Dong Y Y, Xiao C, et al. Impact Abrasive Wear Property of CrAlN/TiSiN Multilayer Coating at Elevated Temperatures[J]. *Materials*, 2022, 15(6): 2214-2214.
- [24] Jie S, An S, Pengjiao Z, et al. Microstructure, mechanical performance, thermal stability, and oxidation resistance of AlCrN/AlCrBN nano-multilayer coating[J]. *Surface and Coatings Technology*, 2024, 493: 131301.