International Journal of Extreme Manufacturing

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To cite this article: Jiaxiang Zhang *et al* 2026 *Int. J. Extrem. Manuf.* **8** 032006

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International Journal of Extreme Manufacturing
Int. J. Extrem. Manuf. **8** (2026) 032006 (28pp)
https://doi.org/10.1088/2631-7990/ae366e

Topical Review

Self-adaptive coated cutting tools: a critical review

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Received 26 February 2025, revised 28 August 2025
Accepted for publication 9 January 2026
Published 2 February 2026

Abstract

The rapid development of advanced engineering materials has pushed cutting operations into regimes characterized by extreme thermomechanical loads, revealing the limitations of conventional coated tool systems. To address these operational challenges, self-adaptive coating technologies have been developed to enable real-time modulation of performance under dynamic machining conditions. These coatings exhibit autonomous structural and functional responses to harsh working environments, thereby preserving cutting performance across a wide range of conditions. This review provides a critical assessment of self-adaptive coated cutting tools, focusing on two principal categories: self-organizing and self-lubricating systems. The preparation methods, cutting conditions, and degradation mechanisms of self-adaptive coatings are summarized and discussed. The respective advantages and limitations of each coating type are evaluated to inform their practical application and guide further development. Finally, a summary and outlook are presented to highlight future research directions in the field of self-adaptive coated cutting tools.

Keywords: self-adaptive coating, cutting tools, extreme cutting conditions, self-organizing, self-lubricating

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1. Introduction

Advanced structural materials, including high-performance ceramics, titanium alloys, nickel-chromium superalloys, and refractory metals (e.g., tantalum), exhibit unique combinations of thermomechanical properties such as elevated temperature strength retention, exceptional chemical inertness, and superior wear resistance[1–6]. Efficient machining of these challenging materials is critical for advancing key industrial sectors, particularly in aerospace propulsion systems, airframe manufacturing, and high-performance automotive applications[7–12]. A fundamental challenge in machining these advanced alloys arises from the simultaneous generation of intense mechanical stresses (exceeding 2–3 GPa) and thermal loads (600–1 200 °C) at the tool-workpiece interface, leading to extreme frictional interactions that accelerate tool degradation mechanisms[13,14]. Therefore, high-performance cutting tools are a crucial foundation for processing advanced engineering materials, as illustrated in Figure 1.

Traditional uncoated cutting tools often encounter issues such as adhesion, thermal effect, and chemical reactions, which result in short tool life, unstable processing quality, and high production costs[15]. Abrasive wear, adhesive wear, diffusion wear, and oxidation wear are the four principal wear mechanisms in cutting tools[16,17]. The advent of tool coating technology in the 1960s is regarded as the lowest cost and most effective approach to extend tool life by three to five times. Applying suitable coatings on the tool surface can significantly mitigate the four main types of tool wear[18–21]. First, coatings act as chemical and thermal barriers, separating the tool from the workpiece and effectively inhibiting diffusion wear and oxidation wear. Second, coatings with a low friction coefficient can greatly reduce adhesive wear. Third, the high hardness of coatings can effectively decrease abrasive wear. Coated tools comprise a composite coating-substrate system. The machining performance of coated tools depends on both the coating and the substrate, as well as their combined response to the machining environment. The surface action mechanism of the workpiece-coating system under extreme machining conditions is shown in Figure 2.

Traditional tool coatings primarily deliver singular functions. For example, titanium nitride (TiN) coatings are applied to reduce surface friction between the tool and workpiece[22], titanium carbide (TiC) coatings enhance abrasive wear resistance[23], and aluminum oxide (Al_2O_3) coatings serve as thermal barriers[24]. With advancements in coating technology, elements such as Al, Cr, Si, Ta, Y, Zr, Hf, and Mo have been incorporated into traditional systems to enhance mechanical properties, high-temperature oxidation resistance, and lubrication performance[25–32]. Meanwhile, coating structures have evolved from early single layers to multi-layers, soft-hard combinations, nano-multilayers, gradients, and nano-composite structures[15]. However, although newly improved coatings achieve multiple or enhanced singular functions, they lack self-adaptive properties. In the 1990s, the tribology team at the United States Air Force Institute first proposed the concept of self-adaptive coatings (also referred to as chameleon coatings)[33,34]. Self-adaptive coatings exhibit automatic structural and chemical adaptation to the working environment[34–41], driving the evolution of tool coatings from traditional functional systems to adaptive ones. When used as cutting tool coatings, self-adaptive coatings can automatically adjust their properties or structure in response to environmental or cutting conditions, allowing coated tools to meet diverse operating environments and machining requirements[42–45]. As shown in Figure 3, self-adaptive coated cutting tools demonstrate the capability to dynamically generate protective films or novel structures in response to stimuli such as temperature, load, pressure, and frictional forces during machining. This adaptive behavior enables coated cutting tools to maintain superior cutting performance under extreme operating conditions and extends tool lifespan.

Self-adaptive coated cutting tools have become a major research focus in recent years. This paper provides a comprehensive overview of research progress on adaptive coating tools. The overall framework of this review is shown in Figure 4. First, a detailed overview is provided for self-organizing functional coated cutting tools and self-lubricating functional coated cutting tools. Self-organization is a primary phenomenon during the friction process of self-adaptive coated cutting tools. Its main feature is the formation of tribofilms or secondary structures on the friction surface, which deliver protection, lubrication, and thermal insulation[46–48]. Self-lubricating coated cutting tools are a new category in which a lubricating coating on the tool surface forms a lubricating film during cutting, thereby reducing friction and wear[49–51]. Second, the preparation methods, cutting conditions, and deterioration mechanisms of self-adaptive coated cutting tools are summarized and discussed. The advantages and limitations of each coating type are thoroughly examined, providing insights into practical applications and potential improvements. Finally, the future development of self-adaptive coated cutting tools is discussed.

2. Self-organizing coatings

2.1. Nanostructured coatings

Nanostructured coatings represent an important strategy for preparing self-adaptive coatings. Compared with conventional coatings, nanostructured coatings offer optimized performance enhancements[54–56]. These coatings can be categorized into nano-multilayer coatings and nanocomposite coatings[57–59]. Nano-multilayer coatings consist of alternating nano-layers with different characteristics, as shown in Figure 5(a). The chemical composition, crystal structure, and hardness of these nano-layers can be adjusted, which improves the coating properties and enhances wear resistance[60]. Nanocomposite coatings generally exhibit superior high-temperature performance and cutting efficiency[61–63]. For

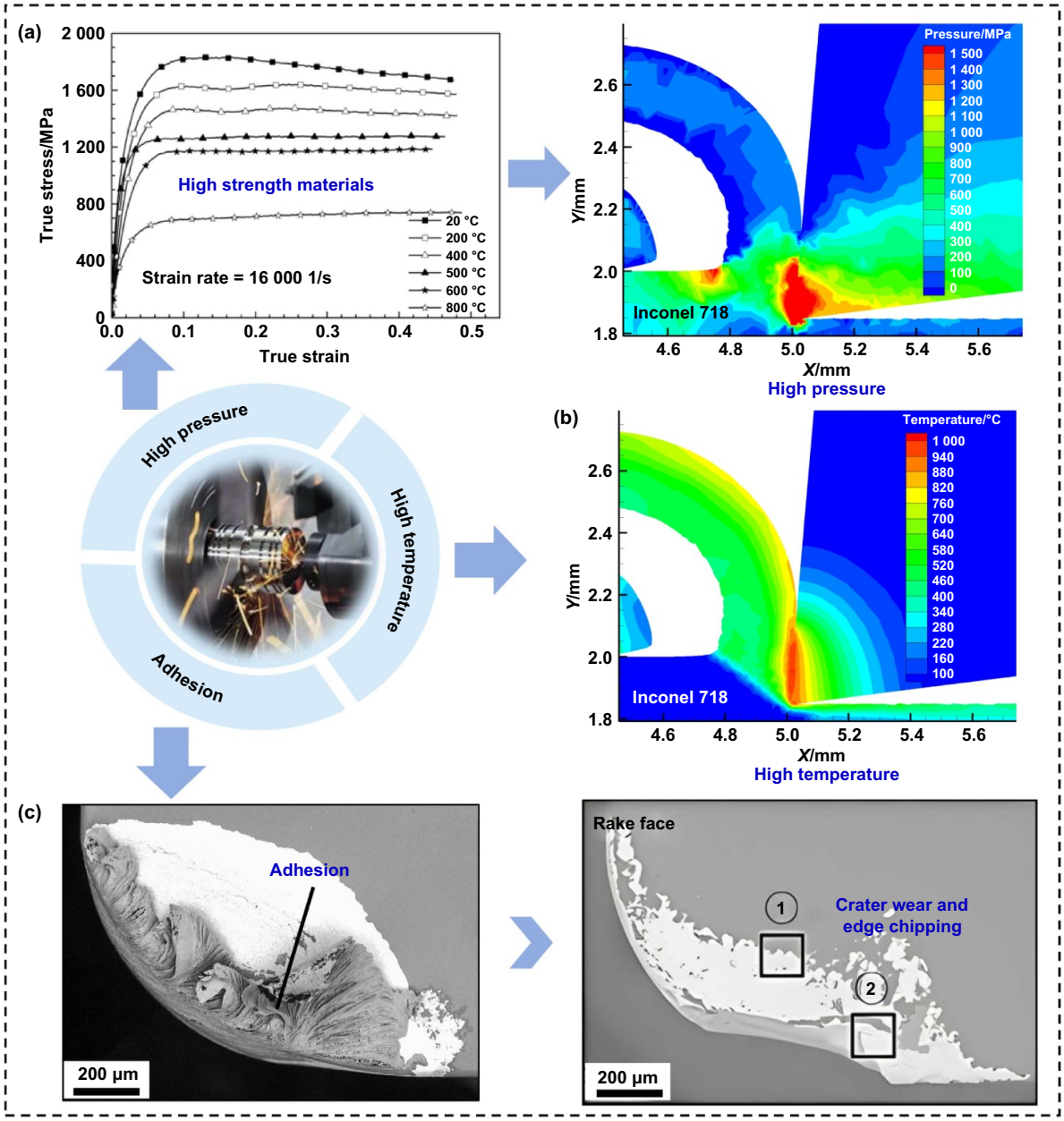


Figure 1. Extreme cutting conditions: (a) high pressure; (b) high temperature; (c) adhesion and wear.

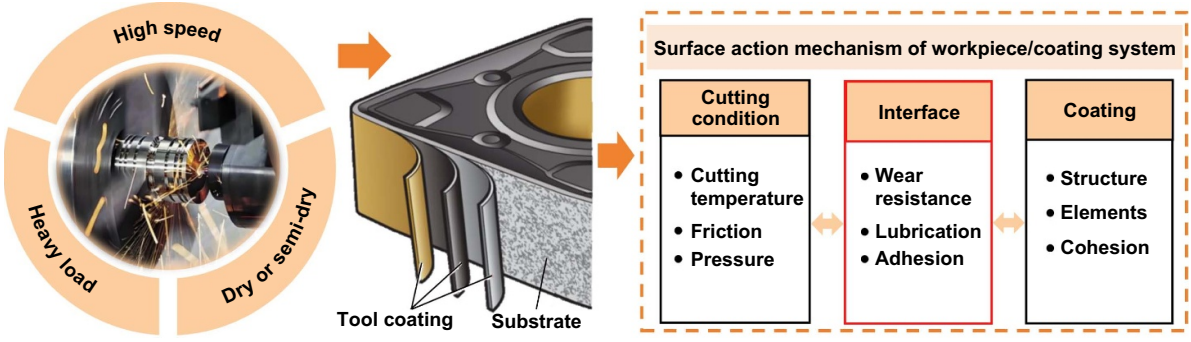


Figure 2. Schematic diagram of the surface action mechanism of coated cutting tools matching the machining conditions.

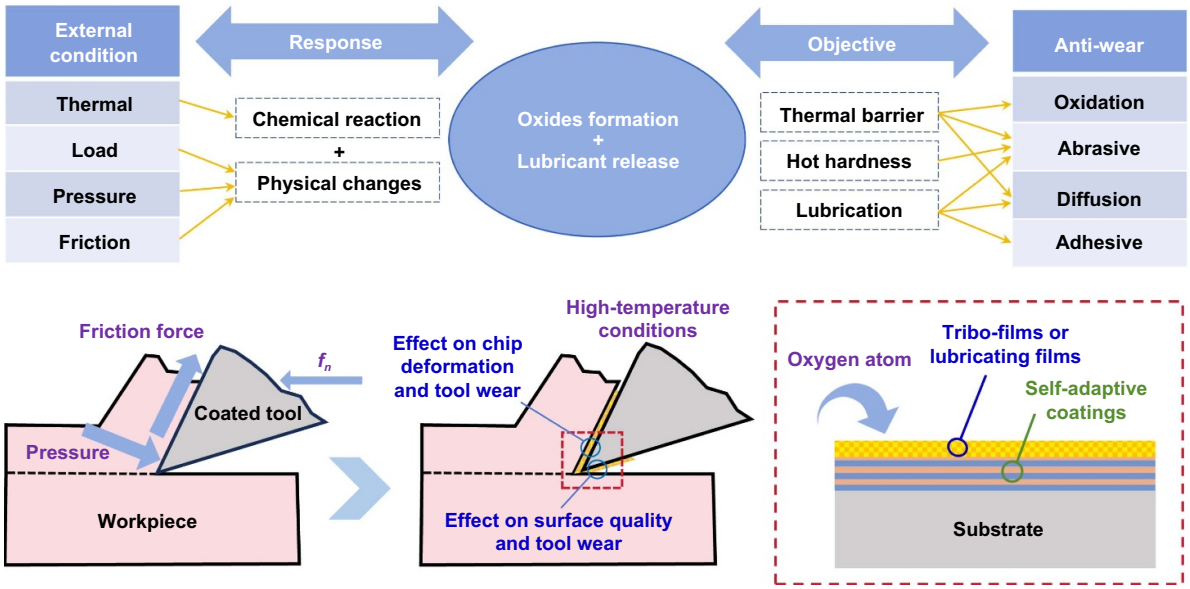


Figure 3. Self-adaptive behavior diagram of coated cutting tools in the cutting process.

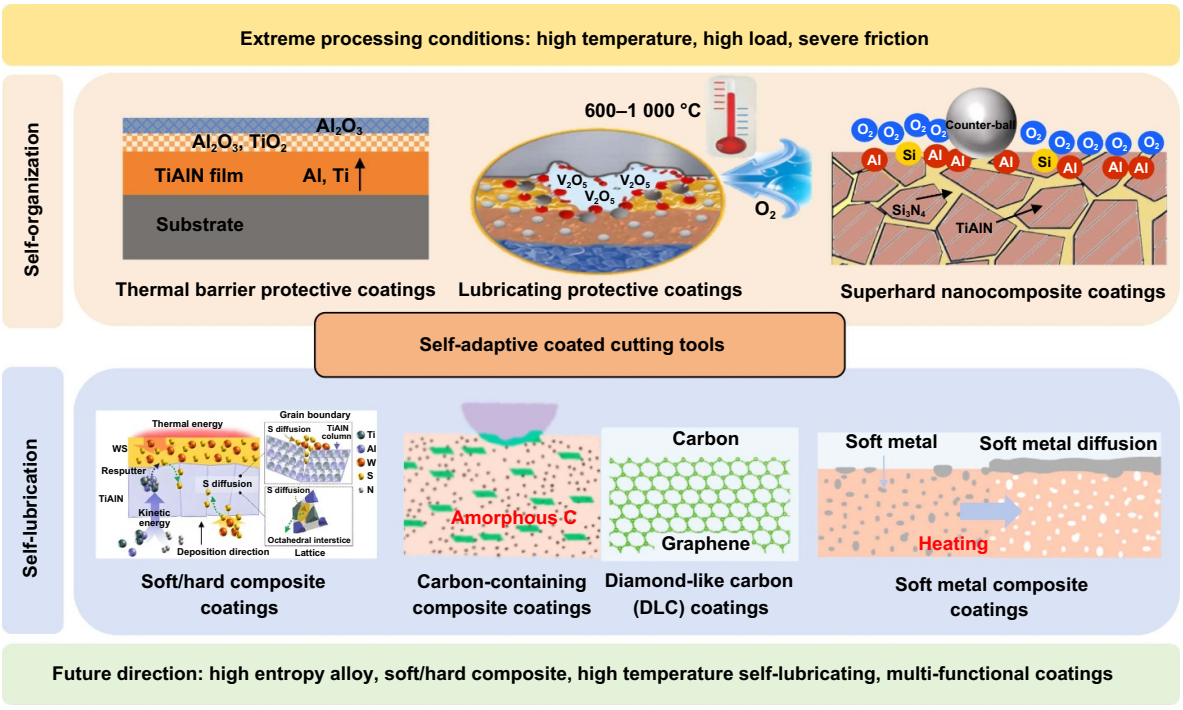


Figure 4. Framework diagram for classification of self-adaptive coated cutting tools[51–53]. Reprinted from[51], Copyright (2020), with permission from Elsevier. Reprinted from[52], Copyright (2016), with permission from Elsevier. Reprinted from[53], Copyright (2021), with permission from Elsevier.

example, the X–Si–N series coatings (where X = Ti, Cr, TiAl, CrAl, etc.) are typical nanocomposite coatings. Incorporating an appropriate amount of silicon into single-phase coatings such as TiN and TiAlN induces thermodynamic spinodal decomposition. This results in a skeletal nanocomposite structure of nanocrystalline transition metal nitrides encapsulated by a Si_3N_4 amorphous atomic layer[64], as illustrated in Figure 5(b). The nanocrystal strengthening effect, combined with grain boundary confinement from the amorphous phase, markedly increases the hardness of nanocomposite coatings beyond that of traditional hard coatings[57,64]. In addition, nanocomposite coatings demonstrate significant improvements in structural stability, thermal hardness, and oxidation resistance at elevated temperatures[65–67].

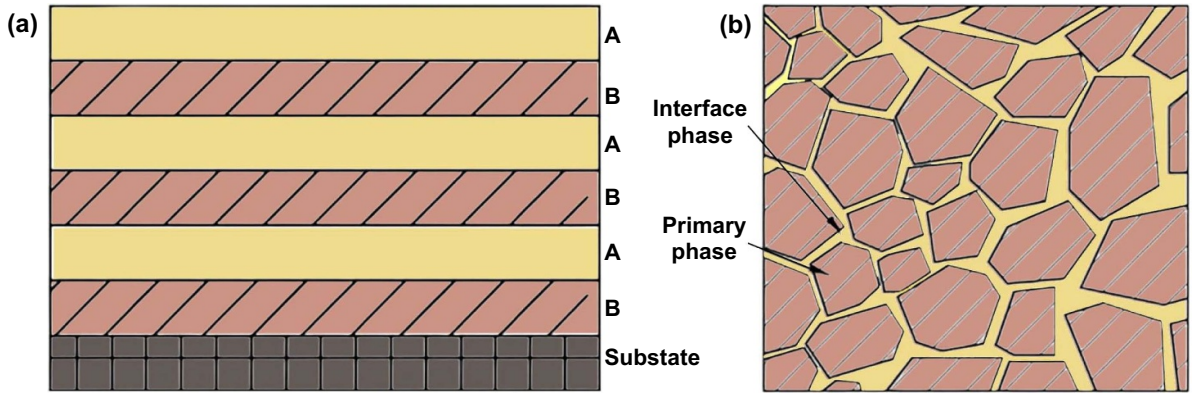


Figure 5. Nano-coating structure diagrams: (a) nano-multilayer coatings; (b) nanocomposite coatings.

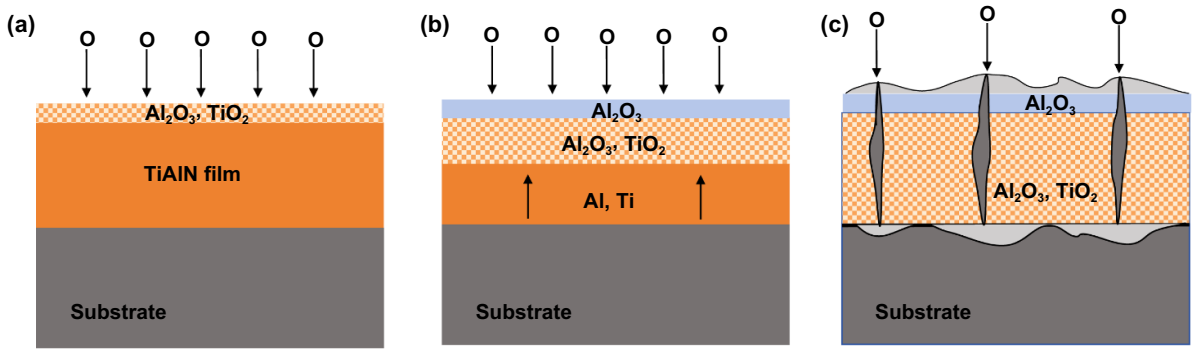


Figure 6. Oxidation diagrams of TiAlN coatings at different temperatures: (a) 500–600 °C; (b) 700–800 °C; (c) >900 °C.

2.2. Thermal barrier protective tribo-oxides coatings

Initially, researchers proposed an alloying strategy to develop new hard coatings with higher hardness and improved oxidation resistance[68]. The TiAlN coating is a notable outcome of this alloying approach[26,69]. Compared with TiN coatings, TiAlN exhibits significant improvements in both hardness[70] and oxidation resistance[71]. TiAlN coatings with high aluminum content and a nanocrystalline structure can self-organize to form an amorphous Al_2O_3 protective film with a low oxygen diffusion coefficient on the coating surface during high-temperature oxidation[72]. This layer inhibits oxygen penetration into the underlying film or substrate, thus providing excellent thermal stability, with oxidation resistance temperatures exceeding 800 °C[73]. At oxidation temperatures below 500 °C, TiAlN coatings show minimal oxidation, as depicted in Figure 6(a), with the coating mainly exhibiting its inherent high wear resistance[73–75]. At approximately 800 °C, the TiAlN coating undergoes oxidation, rapidly forming a protective Al_2O_3 layer on its surface, as shown in Figure 6(b), resulting in exceptional oxidation resistance and hot-hardness. However, when the temperature exceeds 900 °C, the TiO_2 and Al_2O_3 particles produced by oxidation expand in volume, increasing internal stress in the film and leading to defects such as pits and cracks. This process ultimately causes coating failure, as illustrated in Figure 6(c). The oxidation temperature of a coating is a critical performance indicator, as oxidation resistance directly affects applicability in cutting operations. During machining of high-temperature alloys, cutting temperatures can exceed 1 000 °C. As the oxidation resistance temperature of TiAlN coatings is only 800 °C, they may not meet such machining requirements. Increasing the aluminum content in TiAlN coatings can enhance both hardness and oxidation resistance[76–78]. When $0.5 \leq x \leq 0.6$, $Ti_{1-x}Al_xN$ shows optimal mechanical properties and thermal stability. However, if the atomic fraction of Al exceeds 70%, the formation of ω-AlN results in a significant reduction in coating performance[78].

The thermal stability and oxidation resistance of coatings are determined by elemental composition. Alloying elements such as Cr, Si, V, Y, Ta, Mo, Hf, and B are commonly incorporated into TiAlN coatings to improve their overall performance[26–32]. The TiAlCrN system exemplifies this approach[79,80]. The addition of chromium refines the TiAlN microstructure and raises the oxidation resistance threshold above 1 000 °C. At high temperatures, chromium encourages the simultaneous formation of Al_2O_3 and Cr_2O_3 protective layers, thereby improving oxidation resistance and lubrication in Al-depleted regions. Additionally, Zhou et al.[81] investigated the effects of B-doping on the structure, mechanical properties, and thermal behavior of TiAlN coatings. They employed density functional theory (DFT) to evaluate the phase formation energy of cubic and wurtzite structures in $Ti_{1-x-y}Al_xB_yN$ coatings. First-principles calculations indicated that the incorporation of B reduces the solid solubility of

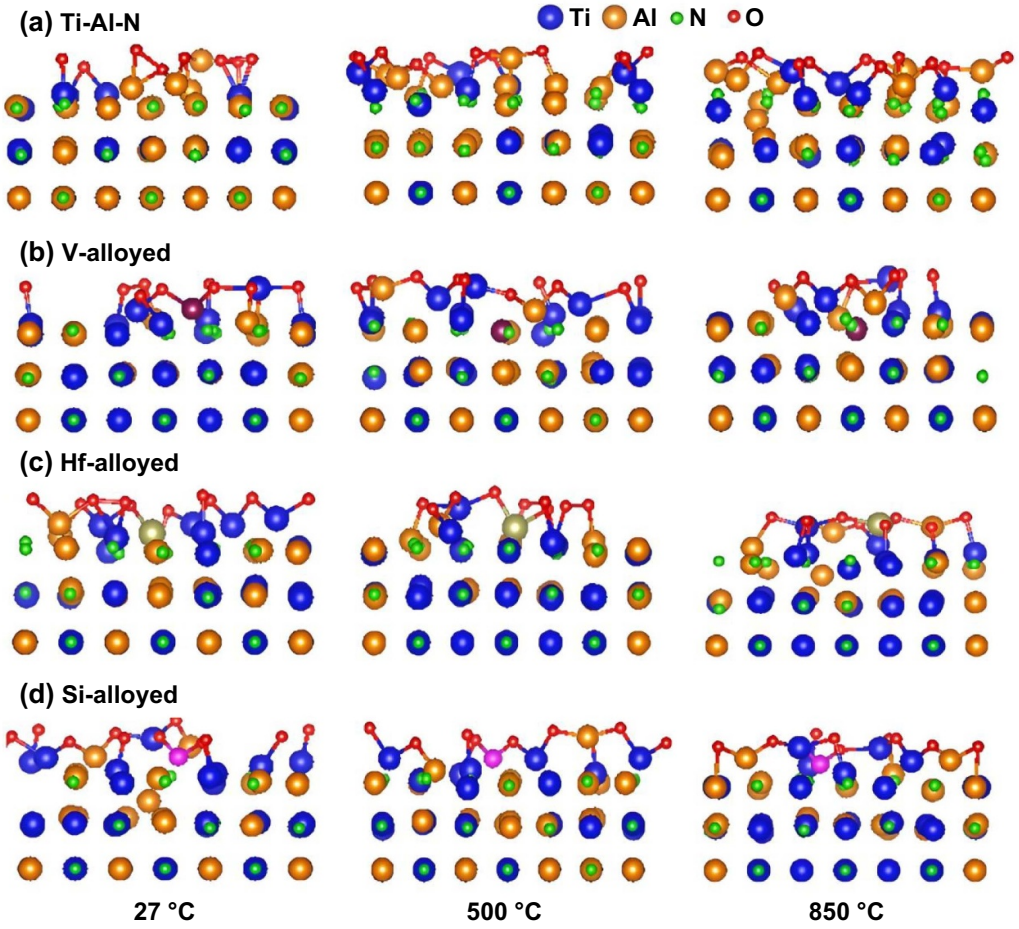


Figure 7. AIMD snapshots of TiAl–X–N (001) surfaces interacting with O atoms after 2 000 fs at room temperature (300 K), 500 °C (773 K), and 850 °C (1 123 K) for (a) TiAlN, (b) TiAlVN, (c) TiAlHfN, and (d) TiAlSiN[83]. Reprinted from[83], Copyright (2020), with permission from Elsevier.

Al in cubic TiN. This finding was used to predict the Al content during the initial formation of wurtzite and to optimize the compositional ratio of alloying elements. Experimental results revealed that the addition of 4 at.% B increases the hardness from (30.1 ± 0.4) GPa for $Ti_{0.44}Al_{0.56}N$ to (32.7 ± 0.9) GPa for $Ti_{0.42}Al_{0.54}B_{0.04}N$. Furthermore, B doping inhibited the transformation of anatase-TiO_2 to rutile-TiO_2 and promoted the formation of α-Al_2O_3, thereby enhancing the oxidation resistance of the TiAlN coating. Similarly, Li et al.[29] studied the influence of Y doping on the thermal stability and oxidation resistance of TiAlN coatings. Both first-principles calculations and experimental results demonstrated that Y doping reduces the solid solubility of AlN in cubic TiAlN and promotes the precipitation of the wurtzite phase. The improved thermal stability of TiAlN with Y incorporation is attributed to the postponed formation of w-AlN along the dominant decomposition sequence TiAlYN → TiYN + AlN → TiN + AlN + YN. The synergistic integration of first-principles calculations and experimental studies serves as an effective guide for the development and optimization of self-adaptive coated cutting tools.

Guo et al.[82,83] provide atomistic insights into the oxidation processes of TiAlN, TiAlVN, TiAlSiN, and TiAlHfN at different temperatures. The diffusion and oxidation of atoms are illustrated in Figure 7. Studies indicate that in high-aluminum TiAlN, the displacement of Al atoms is consistently greater than that of Ti atoms, resulting in surface oxides with an Al-rich top layer and a Ti-rich sublayer at various temperatures. The addition of vanadium promotes bonding between oxygen and titanium while suppressing the activity of aluminum, thus hindering the formation of an Al-rich oxide layer. At high temperatures, vanadium accelerates the breaking of Ti–N bonds, increasing the diffusion of titanium to the surface and the formation of titanium oxides. This disrupts the protective oxide structure, permits inward oxygen diffusion, and reduces oxidation resistance. In contrast, hafnium increases the stability of surface atoms at high temperatures, allowing for layered oxide formation that preserves an Al-rich top layer and a Ti-rich sublayer, effectively suppressing oxygen infiltration. The addition of silicon increases aluminum activity, facilitating the formation of an Al-rich oxide layer. Even if the top layer is not Al-rich, a dense Al-rich oxide layer can still develop in the sublayer, effectively protecting the substrate from oxidation.

On the other hand, microstructure plays a critical role in determining both the thermal stability and oxidation behavior of coatings[84–86]. Nano-layered multilayer coatings

generally demonstrate improved oxidation resistance compared to single-layer coatings. Single-layer coatings are susceptible to oxide formation and phase transformation during heating in air, whereas multilayer nanocoatings exhibit more complex behaviors. In addition to oxidation, nanostructured multilayers undergo complex thermal-induced phenomena when exposed to elevated temperatures. In a comparative study by Zha et al.[87], bilayer and multilayer TiSiN/TiAlN coatings were evaluated for their oxidation and thermal fatigue resistance during Ti-6Al-4V machining. The TiSiN/TiAlN nano-multilayer coating exhibited a distinct elemental distribution, characterized by a dense Al-rich surface layer with underlying layers of other elements. The presence of a dense Al-rich oxide layer substantially impedes the diffusion of oxygen. Researchers also observed that the high density of interfaces and grain refinement within the nano-layered structure promote the formation of a dense, homogeneous, and non-columnar microstructure, thereby enhancing the coating's oxidation resistance. In the turning test of Ti-6Al-4V, the bilayer TiSiN/TiAlN coated tool exhibited edge chipping and cracking, whereas the nanomultilayer TiSiN/TiAlN coated tool showed stable wear with a relatively uniform wear land.

To further improve the protection performance of TiAlCrN coatings, a multifunctional TiAlCrSiYN self-adaptive nanocoating was developed through the addition of silicon and yttrium[45,88]. Silicon refines the grain structure, whereas yttrium prevents the coarsening of densely packed particles at high temperatures and enhances phase stability in Si-containing TiAlCrN coatings[89]. During high-speed machining, the TiAlCrSiYN self-adaptive nano-coated cutting tool surface develops tribo-oxides such as Cr–O, Si–O, Al–O, and Y–O compounds. These oxides exhibit dual functions, combining oxidation resistance with self-lubricating properties. The tribo-oxide layer effectively reduces both the coefficient of friction (COF) and cutting forces, while enhancing the tool's high-temperature oxidation resistance. Another coating, TiAlCrSiYN/TiAlCrN self-adaptive nano-multilayer, has been developed[89]. Compared to commercial TiAlN coatings and TiAlCrSiYN nanocoatings, the TiAlCrSiYN/TiAlCrN self-adaptive nano-multilayer coated tools demonstrate superior tool life in machining Inconel 718 and other nickel-based superalloys. This improvement is primarily attributed to enhanced multifunctionality. The increased cutting life can be explained by reduced build-up edge formation on the cutting edge and decreased intensity of crater wear on the rake surface. Surface analysis of TiAlCrSiYN/TiAlCrN nano-multilayer coatings under extreme friction conditions[90] revealed that high temperature and high load contribute to the self-adaptability of nanocoated tools in the cutting environment. The continuous self-organization of the nanocoating during friction optimizes the wear performance of the tool.

2.3. Lubricating protective tribo-oxides coatings

The lack of lubrication performance at high temperatures is a significant limitation for most hard coatings. TiN and TiC were among the earliest coating materials used in cutting tools[25]. Under high-temperature cutting conditions, TiN and TiC tend to oxidize, forming soft films that serve as solid lubricants. However, when the cutting temperature reaches 500 °C, these coatings undergo significant wear and fail rapidly. Research has demonstrated that the high-temperature frictional properties of coatings can be improved by incorporating elements such as vanadium, molybdenum, and tungsten[91]. For example, the COF of TiAlVN coatings at 700 °C is reduced by 60% compared to TiAlN at room temperature. This improvement is mainly due to the oxidation of vanadium within the coating at high temperatures, which leads to the formation of V_2O_5 Magnéli phases with solid lubricating properties[92,93]. Similarly, TiAlMoN-coated cutting tools exhibit enhanced tribological performance in dry machining, owing to the generation of MoO_3 lubricious phases during cutting. This self-lubricating mechanism enables the coating system to maintain low friction, with a COF ranging from 0.4 to 0.5[94]. Vanadium-based coatings are widely used because they rapidly form V_2O_5, providing lubrication in the cutting zone[95]. Kumar et al.[95] evaluated the tribological performance of TiSiVN-deposited Al_2O_3-SiC ceramic tools during dry machining of Ti-6Al-4 V alloy. Under all conditions, TiSiVN coatings exhibited low surface roughness and lower cutting temperatures. The formation of a V_2O_5 lubricating phase reduces friction and minimizes crater wear. Furthermore, TiAlSiVN-coated cutting tools with different vanadium contents were tested for dry cutting of 316 L austenitic steel[96]. Compared with uncoated tools, those with 11% and 5% vanadium content achieved maximum flank wear reductions of 85% and 67%, respectively. Higher vanadium content further enhances the self-lubricating properties of TiAlSiVN coatings.

Compared to conventional TiAlVN coatings, TiAlN/VN nano-layer coatings possess a denser and more uniform structure, which typically results in better hardness and wear resistance. In earlier studies, an AlTiN/Me_xN nano-multilayer coating with significant lubrication enhancement was reported[44], where Me_x denotes a Group V–VI transition metal. VN and MoN are two promising single-component transition metal nitride films that demonstrate low friction coefficients at elevated temperatures. The principal feature of this nanocoating is its ability to interact with oxygen at high temperatures to form tribo-oxides with superior thermal protection and lubrication[44]. Lubricating oxides not only reduce the COF and frictional force but also transform intense friction into a milder form, greatly improving the wear resistance of cutting tools. Figure 8 shows the self-organization behavior of the TiAlN/VN coating in a high-temperature cutting environment[42]. As shown in Figure 8, when the temperature reaches or exceeds 600 °C, the aluminum and vanadium in the coating interact with oxygen and water vapor in the air, forming Al_2O_3 and V_2O_5 tribo-oxides that provide both thermal protection and high-temperature lubrication.

Luo[97] systematically investigated the friction and wear characteristics of TiAlN/VN nano-multilayer coatings prepared by magnetron sputtering over a wide temperature range from 25 °C to 700 °C. The experimental results show that the friction and wear performance of the coating exhibits a strong dependence on temperature. At low temperatures, both

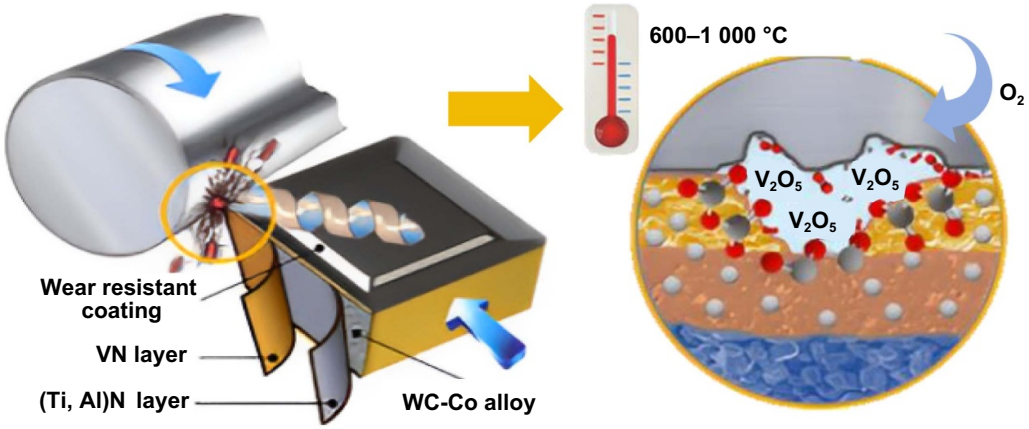


Figure 8. The self-organization behavior diagram of TiAlN/VN multilayer coating during the cutting process[42]. Reproduced from[42]. CC BY 4.0.

the COF and wear rate gradually increase as the temperature rises. When the cutting temperature reaches 400–500 °C, significant oxidation occurs on the coating surface, leading to the formation of a friction film composed of Al_2O_3 and V_2O_5. As the ambient temperature approaches the melting point of V_2O_5 (approximately 633 °C), the friction coefficient of the coating decreases significantly because V_2O_5 serves as an effective solid lubricant. When machining Ti-6Al-4 V alloy, cutting tools coated with TiAlN/VN nano-multilayer exhibit a substantial 50% increase in tool life compared to those with commercial TiAlN coatings[44]. In addition, TiN/MoN and TiAlN/MoN nano-multilayer coated cutting tools prepared by unbalanced magnetron sputtering also display excellent lubrication characteristics during dry cutting[98]. This is because the MoN component in these nanocoatings readily oxidizes and self-organizes to form a MoO_3 surface layer with low shear strength. MoO_3 acts as an effective lubricant, resulting in a low, stable friction coefficient of 0.32 for both types of nano-multilayer coatings.

2.4. Superhard nanocomposite coatings

Nanocomposite coatings with ultra-high hardness and superior properties represent a key direction for the development of advanced tool coatings. Harder coatings are essential as they provide enhanced mechanical and tribological properties, increasing resistance to deformation and wear[99]. A nanostructured coating composed of crystalline Si_3N_4-coated nanocrystals can be synthesized by doping an appropriate amount of silicon into traditional single-phase coatings such as TiN, TiAlN, and CrAlN, as illustrated in Figure 9(a). This innovative nanocomposite coating possesses extremely high hardness and demonstrates excellent adaptability under high-temperature and high-pressure cutting conditions. During cutting, it can self-organize to form protective oxide films such as Al_2O_3, SiO_2, and Cr_2O_3. These oxide films significantly enhance the cutting performance of the coating under extreme friction. Therefore, these nanocomposite coatings are especially suitable for high-speed cutting, dry cutting, and the machining of difficult-to-process materials, contributing to the advancement of modern cutting technology[100,101].

For titanium alloy machining, coating materials such as TiSiN, TiAlSiN, TiCrAlSiN, and TiAlN/TiSiN have been recommended by several manufacturers. A comparison of four TiSiN-based nanocomposite coatings—TiSiN, TiCrSiN, TiAlSiN, and TiCrAlSiN—shows that TiSiN exhibits the highest hardness (34.9 GPa) and Young's modulus[20]. Adding Al or Al/Cr to TiSiN reduces the hardness of the coatings, but this does not diminish their overall effectiveness. The longer tool life of TiAlSiN and TiCrAlSiN coatings compared to TiSiN and TiCrSiN is attributed to the self-organization of Al_2O_3 and Cr_2O_3 lubricating phases on the tool surface during cutting, which improves wear resistance. TiAlSiN coatings have demonstrated exceptional performance under extreme manufacturing conditions due to their high hardness, thermal stability, and enhanced wear resistance. This improvement in mechanical properties is attributed to the nanocomposite configuration, in which TiAlN acts as a reinforcing agent within the Si_3N_4 matrix, generating coatings with higher hardness than standard TiAlN, AlTiN, and AlCrN coatings. The amorphous Si_3N_4 phase plays several roles in the coating[102,103]. It effectively refines the grain structure, inhibits excessive grain growth, increases grain boundary density, and optimizes the coating microstructure. In addition, Si_3N_4 suppresses the formation of the h-AlN phase, thereby further improving thermal stability. The tribological properties of TiAlSiN coatings at various temperatures have been systematically investigated[52]. At room temperature, as shown in Figure 9(b), Si reacts with atmospheric moisture to form $SiO_2{\cdot}nH_2O$, which reduces friction during sliding. At 600 °C, Al and Si atoms migrate to the surface, forming a dense protective layer of Al_2O_3 and SiO_2, as shown in Figure 9(c). This layer not only resists environmental attack but also provides excellent lubrication, ensuring stable coating operation at elevated temperatures. At 800 °C, as shown in Figure 9(d), the TiAlSiN coating forms Al_2O_3 and SiO_2, as well as TiO_2 rutile with low shear strength, further improving lubrication.

Similarly, introducing Si into CrAlN coatings can improve mechanical properties through solid solution strengthening

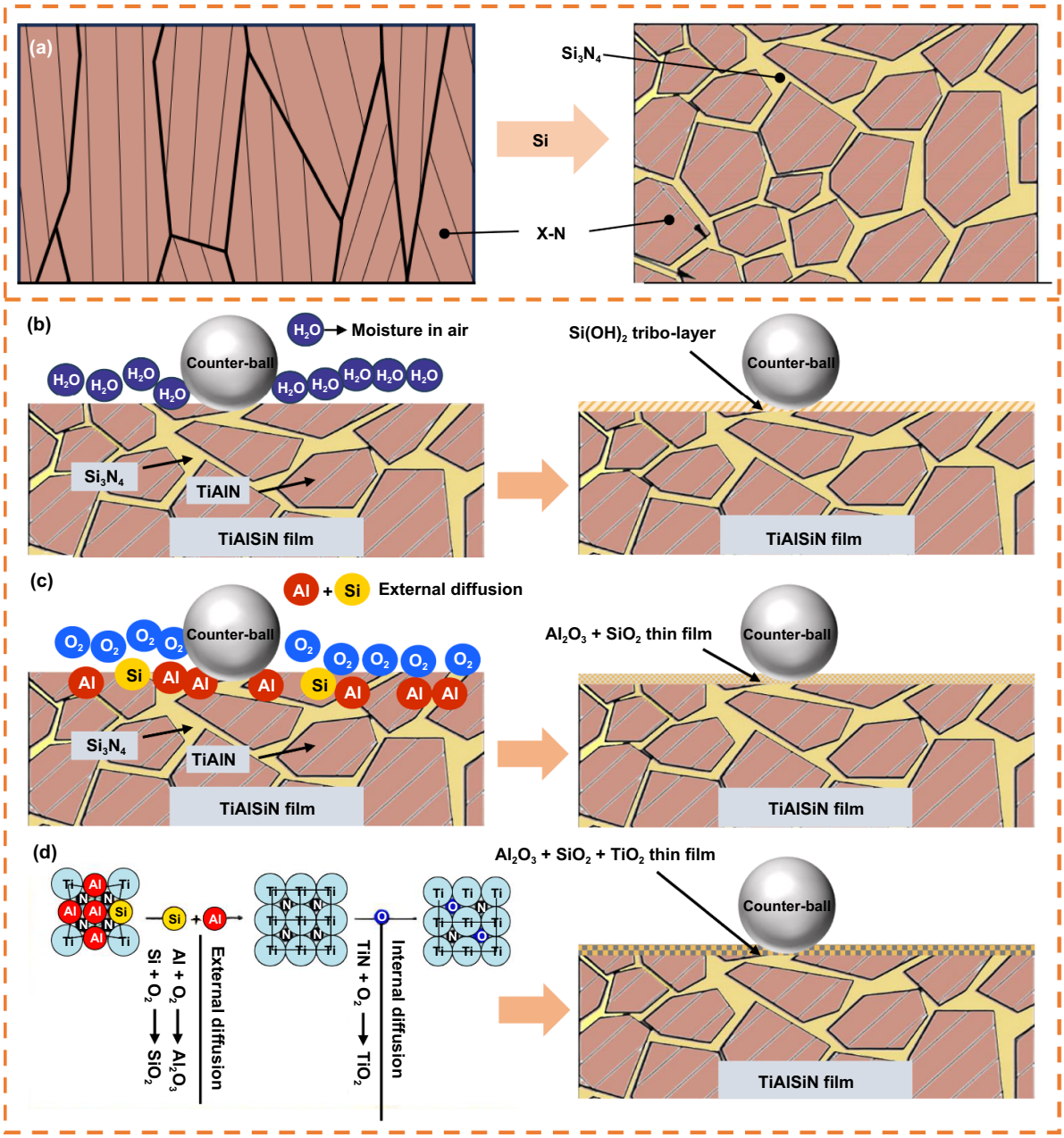


Figure 9. Schematic diagram of: (a) X–N coatings (X: Ti, Cr, TiAl, CrAl, etc.) with Si transformed into an X–Si–N nanocomposite coating structure; (b) $SiO_2 \cdot nH_2O$ transfer film formed during sliding at room temperature; (c) mixed oxide film of Al_2O_3 and SiO_2 at 600 °C, and (d) mixed oxide film of Al_2O_3, SiO_2, and TiO_2 at 800 °C[52]. Reprinted from[52], Copyright (2016), with permission from Elsevier.

and grain refinement[67,104]. Owing to different Al and Si contents, CrAlSiN coatings show varied microstructures, resulting in significant differences in mechanical properties[105]. Variations in deposition technique can also produce substantial disparities. For example, CrAlSiN coatings deposited by multi-arc ion plating exhibit superior hardness, reaching up to 52 GPa[106]. In contrast, those deposited by unbalanced magnetron sputtering with approximately 4.5% Si content (atomic fraction) achieve a maximum hardness of only 39 GPa[107]. Studies show that as Si content increases, the hardness of CrAlSiN coatings first increases and then decreases[108,109]. This trend is mainly determined by the solid solubility of Si in the coating and its chemical interactions with Cr and Al[110,111]. This finding offers important guidance for optimizing the composition of CrAlSiN coatings and enhancing their mechanical properties. Modern manufacturing environments require surface coatings to possess a comprehensive set of mechanical properties. While high hardness and excellent wear resistance remain essential, these protective layers must also maintain sufficient impact resilience to withstand varying loading conditions characterized by broad frequency and amplitude ranges[112].

2.5. High entropy alloy (HEA) coatings

High-entropy alloys (HEAs) are defined as alloys containing five or more elements, each with an atomic fraction between 5% and 35%[113,114]. These materials exhibit unique characteristics such as high-entropy, lattice distortion, sluggish diffusion, and the "cocktail" effect, resulting in high hardness, excellent wear resistance, outstanding high-temperature oxidation resistance, and corrosion resistance[113–116]. HEA thin films achieve not only high hardness but also good toughness and plasticity, making them particularly suitable for high-speed cutting tool applications[117]. Shen et al.[118] studied the hardness and stability of the $(Al_{0.34}Cr_{0.22}Nb_{0.11}Si_{0.11}Ti_{0.22})_{50}N_{50}$ nitride coating. They found that it retained high hardness after annealing in both vacuum and air. Although hardness decreased to 26 GPa after annealing at 1 000 °C for 2 hours in vacuum, this value remained higher than that of conventional TiN coatings used in industry. Additionally, after annealing in air at 1 000 °C for 2 hours, the coating's microstructure and phases showed no significant change, indicating excellent thermal stability. A dense oxide film formed on the surface during annealing in air, resulting in only a slight change in hardness (from 31 GPa to 33 GPa). Compared with commercial TiN- and TiAlN-coated tools, tools coated with this high-entropy nitride (HEN) showed lower flank wear during milling tests on SKD11 and 304 stainless steels.

Currently, HEA coatings remain at the research stage, with relatively few studies specifically addressing their use in cutting tools. The cutting performance and failure mechanisms of these coatings require further investigation, and the industrial application of HEA coatings on cutting tools continues to present significant challenges.

3. Self-lubricating coatings

3.1. Soft coatings

Soft-coated cutting tools are a category of self-lubricating coated tools with coating hardness below 10 GPa. Their main design objective is to achieve a low friction coefficient, reduce cutting force and temperature, and thus extend tool life[119]. Soft coatings are typically composed of solid lubricant materials with low friction coefficients, including MoS_2, WS_2, CaS_2, TaS_2, WC, and C[119–121]. During machining, a unique tribological phenomenon occurs: the solid lubricant from the tool's coating is transferred to the workpiece interface, forming a protective transfer film[50,51]. This transfer film enables friction to occur mainly between the transfer and lubricating films, rather than directly between the tool and workpiece. This mechanism significantly lowers the friction coefficient, effectively prevents adhesion, reduces both cutting temperature and force, and inhibits the formation of built-up edge[119]. Owing to their ability to maintain favorable tribological properties and chemical stability under challenging conditions, soft-coated cutting tools are widely used in extreme friction environments.

MoS_2 is a layered solid lubricant with a hexagonal structure and is widely used due to its ultra-low friction. However, its use is limited by temperature. Oxidation occurs in MoS_2 soft coatings at temperatures above 400 °C, resulting in the formation of MoO_3 and a substantial loss in lubricating ability[122]. The tribological performance of MoS_2 coatings is also sensitive to atmospheric moisture, with the friction coefficient doubling as relative humidity increases from 10% to 90%[123,124]. WS_2, a novel layered solid lubricant, demonstrates a remarkably low friction coefficient and superior oxidation stability, making it valuable for aerospace and other advanced applications[125]. After 5 min of dry cutting of 45# quenched and tempered steel, abrasive and adhesive wear on WS_2 soft-coated tools are significantly reduced compared to uncoated YT15 tools, as shown in Figure 10(a)[125]. The cutting force and temperature are reduced by 30%–35% and 10%–15%, respectively. The main mechanism for the observed reduction in cutting force and temperature in WS_2-coated tools is the decreased average shear strength at both the tool-chip and tool-workpiece interfaces during machining.

Although soft coatings possess very low friction coefficients, their hardness and wear resistance are generally inferior to hard coatings. Moreover, when used alone on cutting tools, the durability of soft coatings is limited. To improve the wear resistance and maintain the low-friction advantages of soft coatings, micro-texturing techniques have been used to enhance load-bearing capacity and wear resistance[127–129]. For instance, Lian et al.[126] developed a WS_2 soft-coated nano-textured self-lubricating tool (WTT). Compared to traditional tools, the WS_2 soft-coated nano-textured tool displays a significant reduction in cutting force, cutting temperature, and friction coefficient at the tool-chip interface, with improved anti-adhesion performance during dry cutting. The WTT tool features a self-flow lubrication mechanism[130]. During machining, a lubricating layer forms on the tool surface as WS_2 stored in the micro-nano textured grooves is squeezed and dragged out, as shown in Figure 10(b). When the lubricating film is depleted or broken due to high temperature and pressure, as shown in Figure 10(c), WS_2 in the grooves is released to the tool surface, regenerating the lubricating film. The nano-textured design not only delivers excellent lubrication but also significantly improves the durability and stability of the cutting tools.

Additionally, doping metal elements into soft coatings can improve their microstructure as well as their mechanical and tribological properties. Examples include MoS_2/Zr, MoS_2/Ti, MoS_2/Y, WS_2/Cr, and WS_2/Ag[131]. Early research led to the preparation of MoS_2/Zr and WS_2/Zr metal-doped soft-coated cutting tools[131,132]. Compared to uncoated and conventionally soft-coated cutting tools, tools with MoS_2/Zr and WS_2/Zr composite coatings showed reduced cutting forces, lower temperatures, reduced friction coefficients, and decreased tool wear. Recently, Yi et al.[133] investigated the structure and mechanical properties of pure MoS_2 and MoS_2/Y composite coatings deposited by CVD on TiN-coated cemented carbide blades. Their results showed that, compared with MoS_2 coatings, the hardness of the MoS_2/Y composite coating ((7.5 ± 0.4) GPa) was 2.5 times higher, while substrate adhesion ((50 ± 0.9) N) improved by 16 times, primarily due to a denser microstructure. Additionally, the MoS_2/Y composite

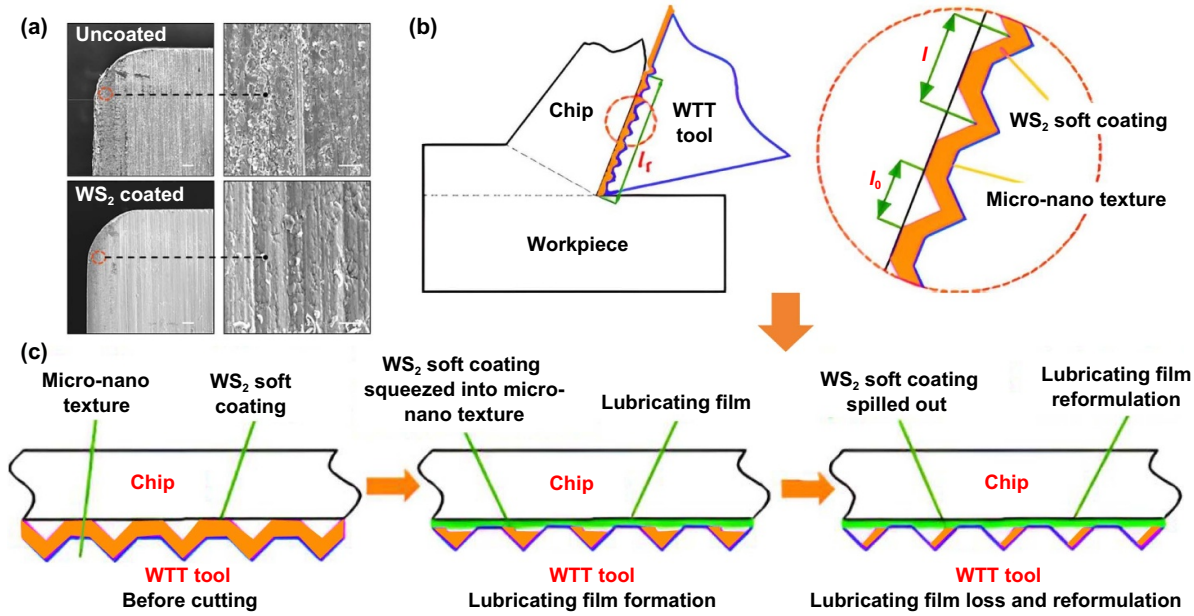


Figure 10. Cutting performance and self-lubricating mechanism of WS_2-coated tool. (a) SEM images of the worn rake face for the uncoated cutting tool and WS_2 soft-coated cutting tool after 5 min of dry machining[125]. Reproduced from[125], with permission from Springer Nature. (b) Cutting tool with nano-textured surface and WS_2 soft coating. (c) Self-lubricating mechanism of WTT tool during cutting[126]. Adapted from[126], with permission from Springer Nature.

coating maintained a friction coefficient of 0.128 after 3 hours of sliding, with a wear rate nearly two orders of magnitude lower than pure MoS_2.

Although soft coatings deliver excellent lubrication, their practical use still faces several limitations. Micro-texture engineering and metal doping are effective strategies to further enhance the performance of soft coatings.

3.2. Soft-hard composite coatings

Compared with hard coatings, soft coatings generally exhibit lower wear resistance. Under high load, high speed, or extreme processing conditions, soft coatings tend to wear more rapidly and cannot sustain self-lubrication over extended periods. Researchers have shown that combining hard and soft coatings can effectively utilize the high hardness and wear resistance of hard coatings together with the superior lubrication of soft coatings[53,134,135]. These composite coatings are designed to overcome the limitations of single-layer coatings, delivering enhanced, multi-functional tool performance to meet the demands of complex machining environments.

The tool life of TiN coatings declines significantly under extreme conditions, such as dry machining and high load[136,137]. The application of a MoS_2 soft coating with self-lubricating capability on top of TiN has proven effective in improving tribological properties and wear resistance[138]. For example, the TiN-MoS_2 soft-coated cutting tool introduced by Guehring of Germany achieved a friction coefficient as low as 0.10[139]. This coating delivers self-lubrication and non-adhesion properties, making it especially suitable for dry or semi-dry drilling of light metal materials such as aluminum and titanium alloys. Furthermore, a CrCN-WS_2 soft-hard bilayer coated cutting tool was developed by Lian et al.[135], as shown in Figure 11(a). Comparative testing revealed that CrCN-WS_2 soft-hard bilayer coated tools (CWT) outperformed both CrCN hard-coated (CT) and WS_2 soft-coated (WT) tools under identical machining conditions, as shown in Figures 11(b) and (c). As indicated in Figure 11(c), a characteristic soft/hard interfacial film forms at the tool-chip contact zone of the composite coating, simultaneously providing lubrication and wear resistance. The synergy of the CrCN hard coating with the WS_2 soft coating not only improves heat dissipation but also substantially reduces cutting forces. This makes the coating particularly effective for high-speed machining of TC4 titanium alloy.

Although the combination of hard and soft layers can significantly reduce friction coefficients, many reported composite coatings show a marked decrease in hardness and adhesion[140,141]. Recently, a TiAlN/WS self-lubricating composite coating with a nano-multilayer architecture was reported[53]. In comparison to general soft-hard composites, the TiAlN/WS coating exhibits stable hardness (14 GPa), a low COF (0.261), and enhanced adhesion (135.4 N). This improvement arises, in part, because sulfur atoms in the amorphous WS layer diffuse into grain boundaries and octahedral interstices of the face-centered cubic (fcc) TiAlN lattice[142]. This disrupts the columnar growth of TiAlN, suppresses crack propagation, and improves the bonding strength and adhesion of the coating, as shown in Figure 12(a). Additionally, as shown in Figure 12(b), the low COF WS layer is capable of forming micron-sized self-lubricating debris. During friction, WS separates from the wear debris, creating amorphous WS that further reduces friction. Wear resistance analysis demonstrated substantial performance advantages of the

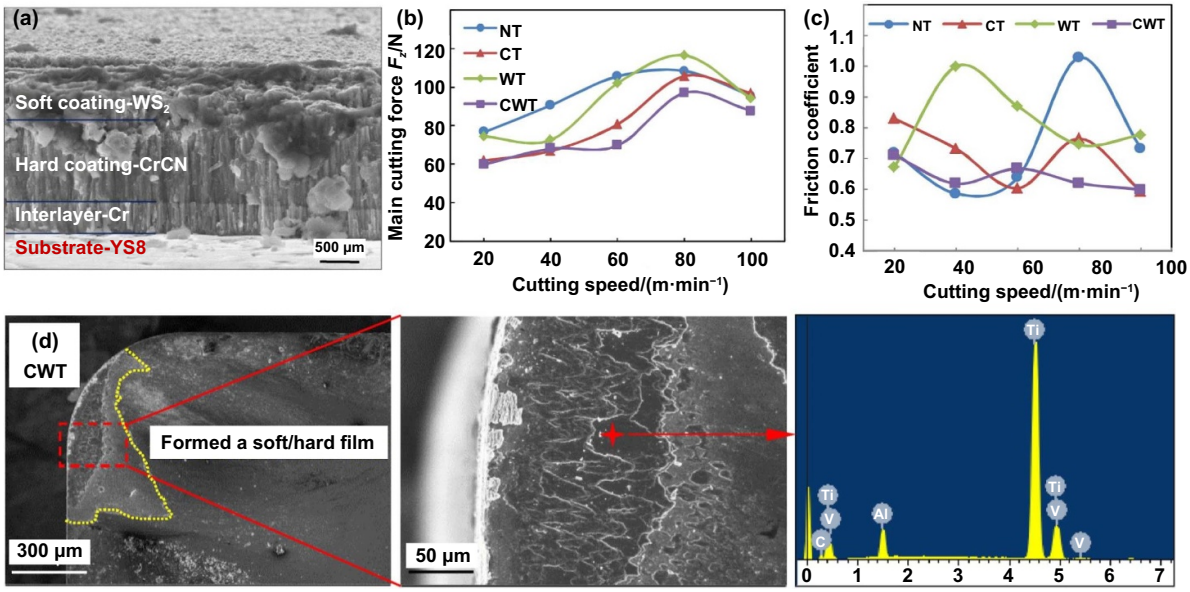


Figure 11. Cutting performance of CrCN-WS_2 soft-hard bilayer coated tools. (a) Cross-sectional micromorphology of the CrCN-WS_2 hard-soft bilayer coating. (b) Main cutting force of various tools at different cutting speeds. (c) Average friction coefficient at the rake face under different cutting speeds. (d) Micrographs of adhesion morphology and composition analysis on the rake face of CWT[135]. Reprinted from[135], Copyright © (2020), with permission from Elsevier.

self-lubricating composite coating over conventional TiAlN coatings under the same machining conditions. Experimental results showed a 200% increase in tool life for the self-lubricating composite compared with TiAlN at a flank wear of 0.3 mm. Moreover, the TiAlN/WS self-lubricating composite coating demonstrated excellent performance in dry machining. The innovative design offers a promising strategy for machining difficult-to-cut materials at high speed and in environmentally friendly applications.

3.3. Diamond-like carbon (DLC) coatings

Carbon materials, especially graphene and diamond-like carbon (DLC), are widely used as lubricating materials, with DLC being a highly prominent carbon-based solid lubricant[51]. DLC is a form of highly sp^3 hybridized carbon that can be deposited at low temperatures. It offers superior wear resistance, high hardness, and self-lubricating properties[143,144]. Therefore, DLC is suitable as a coating for cutting tools. The adhesion strength between DLC coatings and tool substrates is relatively low. A transition layer is usually introduced between the DLC coating and the substrate to balance the thermal expansion and lattice mismatch, thereby enhancing the bonding strength and toughness of the DLC coating.

In low-speed machining under moderate temperatures, DLC coatings reduce friction and suppress heat build-up, making them highly promising for dry and near-dry machining[145]. For example, Pérez-Salinas et al.[145] investigated the tribological properties of DLC coatings sliding against Inconel 718 alloy. The results demonstrated that the DLC coating delivers strong self-lubrication under dry conditions and maintains a low friction coefficient of 0.16 even without external lubricants at room temperature. Ziberov et al.[146] examined the wear of DLC- and TiAlN-coated micro-tools in micro-milling of Ti-6Al-4V alloy. The service life of DLC-coated micro-tools was significantly extended under dry cutting, with wear reductions of 640% and 267% relative to TiAlN-coated and uncoated tools, respectively. Comparative analysis by Sahoo et al.[147] on Ti6Al4V micro-milling further demonstrated the superior performance of DLC coatings compared to TiAlN and TiN coatings. DLC coating reduced cutting forces, burr height, and surface roughness by 22.2%, 35%, and 17.5%, respectively, versus uncoated WC surfaces. DLC-coated tools also achieved the best dynamic stability, increasing the critical stability limit by 17.04%. To further analyze the influence of DLC coating thickness on high-speed micro-milling, Sahoo et al.[148] deposited DLC coatings with thicknesses of 440, 640, and 1 160 nm on micro end mills using a cathodic arc system. The findings revealed that DLC coatings enhance the hardness and wear resistance of WC tools, reduce the friction coefficient and cutting force, and minimize edge chipping, as shown in Figures 13(a)–(d). Among the tested coatings, the 640 nm DLC layer provided the best cutting performance. When the DLC coating is too thin, rapid delamination exposes the substrate to wear. When the coating is too thick, the increased edge radius causes excessive friction and plowing, which accelerates tool wear.

Considering the potential application of DLC-coated tools in Al–Si alloy machining, Du et al.[149] investigated the cutting performance of Cr/W-DLC/DLC-coated tools through finite element simulations combined with experimental validation. The results indicated that the Cr/W-DLC/DLC-coated tool exhibited the lowest cutting forces and cutting temperature, as well as lower film-substrate interface temperature and stress, compared to TiC-, Al_2O_3-, and TiAlN-coated tools. As the cutting speed increased, the peak temperature location on the rake

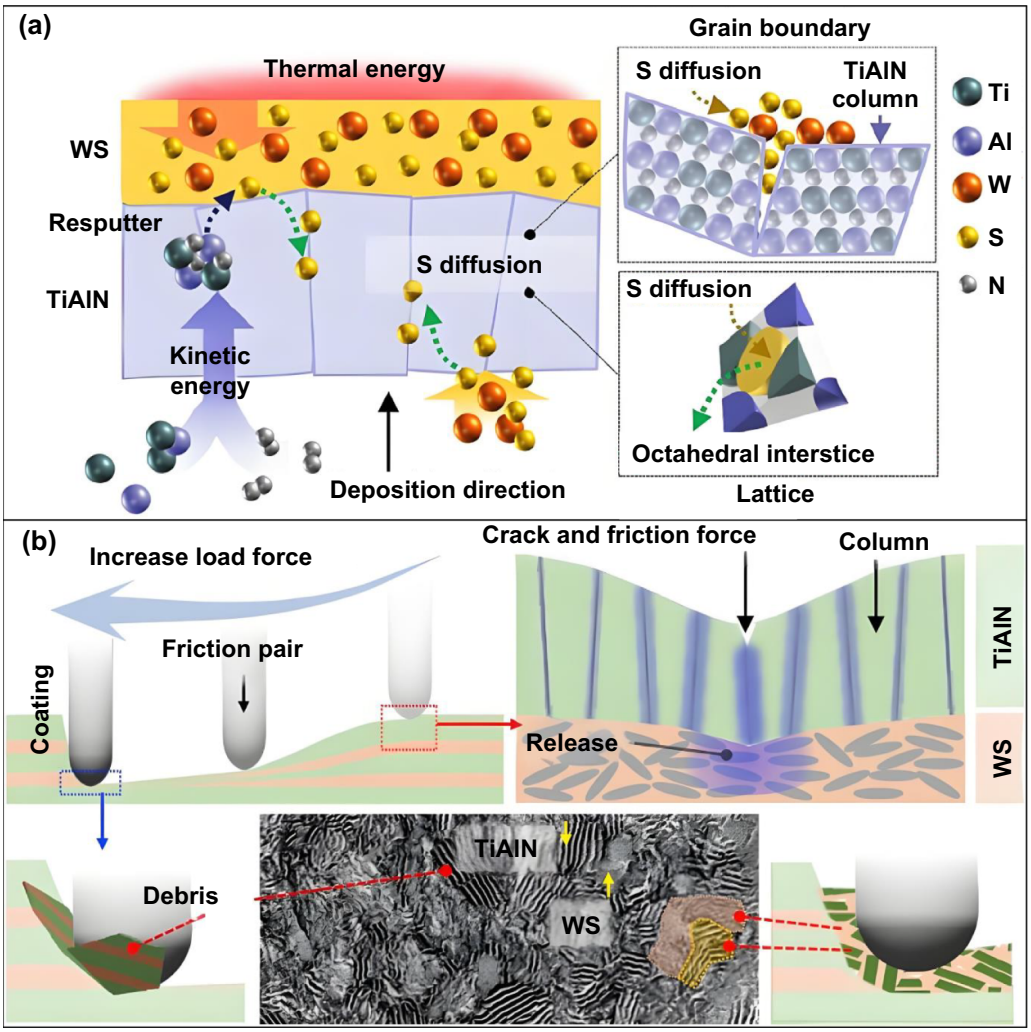


Figure 12. Self-adaptability of TiAlN/WS composite coatings[53]. (a) Schematic of S atom diffusion mechanisms within the composite coating. (b) Schematic explanation of the factors contributing to low COF and enhanced adhesion of the self-lubricating coatings. Reprinted from[53], Copyright © (2021), with permission from Elsevier.

face of the Cr/W-DLC/DLC-coated tool shifted closer to the tool tip, indicating that a greater amount of heat was carried away by the chips. Furthermore, the increase in cutting speed also significantly reduced the depth of plastic deformation on the machined surface. As the cutting speed increased from 400 m·min^{-1} to 2 000 m·min^{-1}, the maximum depth of plastic deformation on the machined surface decreased from 0.16 mm to 0.05 mm. The finite element method (FEM) provided access to data that are difficult to obtain through experimental cutting tests, thereby offering a basis for the development and practical application of Cr/W-DLC/DLC-coated tools.

3.4. Carbon-containing composite coatings

The incorporation of carbon enhances both the mechanical and tribological properties of coatings[150–152]. While the addition of aluminum favors thermal stability, carbon effectively reduces friction coefficients. When both Al and C are added to TiN coatings, the resulting material exhibits high hardness (40 GPa), excellent thermal stability, and outstanding tribological performance[153]. This improvement is primarily attributed to the formation of a transfer film during friction, which combines the lubricating effect of amorphous carbon with the synergistic action of metal oxides. During cutting, aluminum in the TiAlCN coating self-organizes to form Al_2O_3, which effectively inhibits oxygen diffusion into the coating and improves high-temperature oxidation resistance. Carbon in the TiAlCN coating exists as crystalline compounds or amorphous carbon, both of which contribute to enhanced friction and wear resistance[154].

A key factor in coated tool failure during high-speed cutting of titanium alloys is the high friction coefficient, which leads to extremely high temperatures at the contact zone[53]. To address the requirements for high-speed machining of titanium alloys, Li et al.[155] prepared TiAlCN coatings with a low friction coefficient (0.231) and high adhesion (156 N) using magnetron sputtering. At a cutting speed of 100 m·min^{-1}, TiAlCN coatings showed significantly reduced adhesion wear and a cutting distance 200% longer than uncoated tools and 50% longer than TiAlN-coated tools, as illustrated in Figure 14(a).

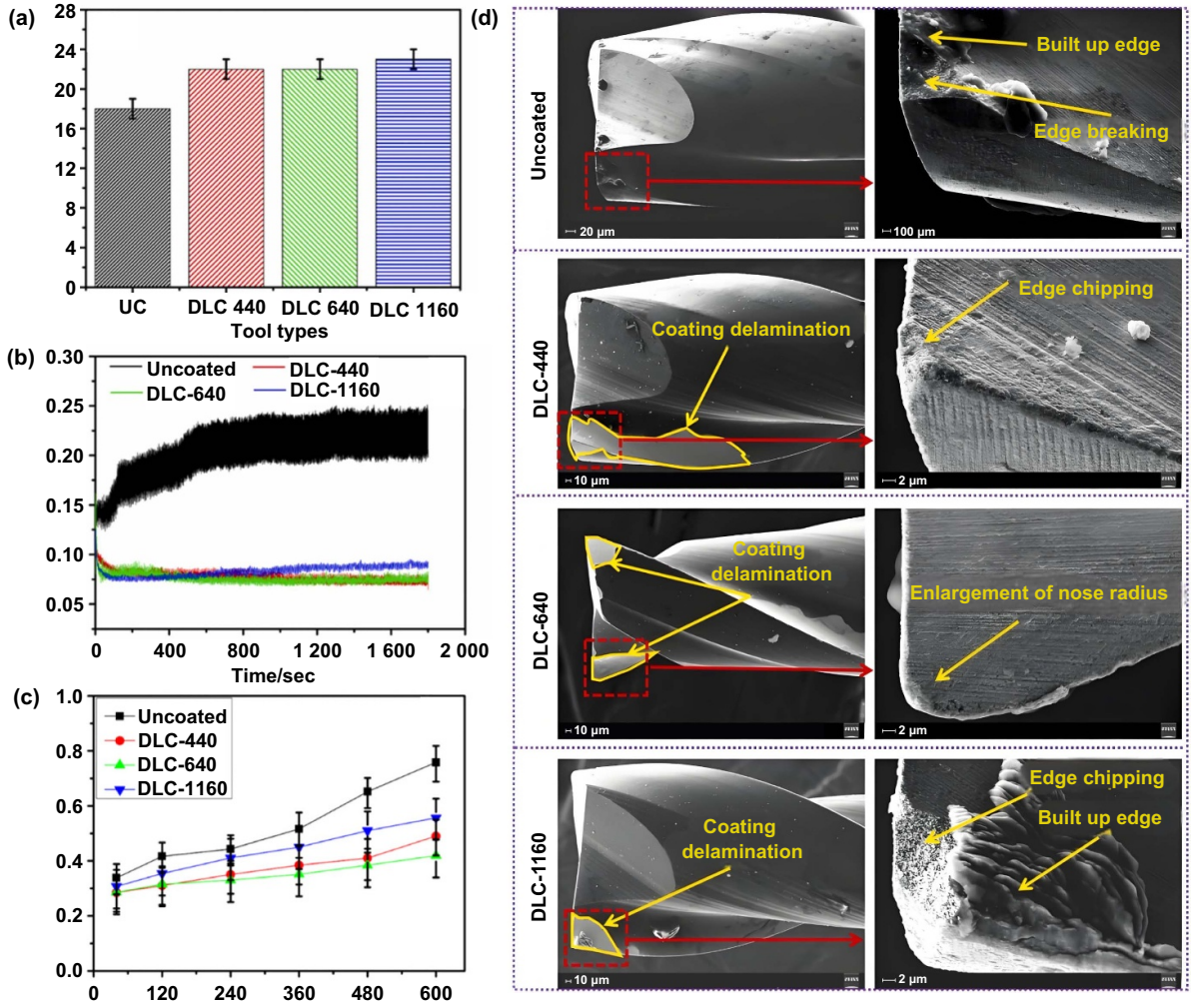


Figure 13. Performance of tools with different DLC coating thicknesses[148]. (a) Hardness. (b) Variation of COF with time. (c) Cutting force variation with machining length. (d) FESEM images of the front view of DLC-coated and uncoated tools after a machining length of 600 mm. Reprinted from[148], Copyright © (2024), with permission from Elsevier.

While TiAlCN coatings provide much longer service life in high-speed titanium alloy cutting compared with TiAlN, their high-temperature performance remains limited. To address this, Li et al.[156] prepared a TiAlTaCN coating with high-temperature lubricating properties by introducing tantalum. The thermal stability of this coating was improved from 600 °C to 1 000 °C. Under high-speed cutting conditions, the cutting distance of TiAlTaCN-coated tools increased by 250% compared with TiAlCN. This performance enhancement is mainly due to the oxidation behavior of the TaN and TaC phases. TaN oxidizes easily to form protective Ta_2O_5, compensating for the insufficient oxidation resistance of Al_2O_3, while the oxidation-resistant TaC phase, in combination with the amorphous carbon phase, achieves self-lubrication. The high-temperature oxidation behavior of TiAlTaCN coatings is depicted in Figure 14(b).

Nanocomposite coatings such as TiSiN and TiAlSiN have attracted significant interest due to their superior oxidation resistance, thermal stability, and ultra-hardness[52]. However, these transition metal nitride-based coatings inherently lack solid lubrication and tend to have higher coefficients of friction. Introducing carbon into these nanocomposite coatings is an effective approach for enhancing their tribological properties and achieving a self-lubricating effect. For instance, Li et al.[158] developed TiSiCN coatings with ultra-high hardness (43.6 GPa) and a low friction coefficient (0.3) by arc ion plating. Wang et al.[159] demonstrated that moderate carbon content in TiSiCN coatings led to excellent lubrication and improved wear resistance. Li et al.[157] fabricated TiAlSiCN coatings with outstanding high-temperature wear resistance using magnetron sputtering. Adding suitable amounts of Si and C significantly enhanced performance: the amorphous SiNx phase improved hardness and wear resistance, while the self-lubricating amorphous carbon phase reduced the wear rate. Figure 14(c) illustrates the wear behaviour schematic diagram of the TiAlSiCN after friction at different temperatures. In high-speed titanium alloy cutting, the cutting life of $Ti_{24.5}Al_{20.6}Si_{4.2}C_{26.2}N_{24.5}$ coated tools was extended by 120% over TiAlCN-coated tools and by 225% over commercial TiAlN-coated tools.

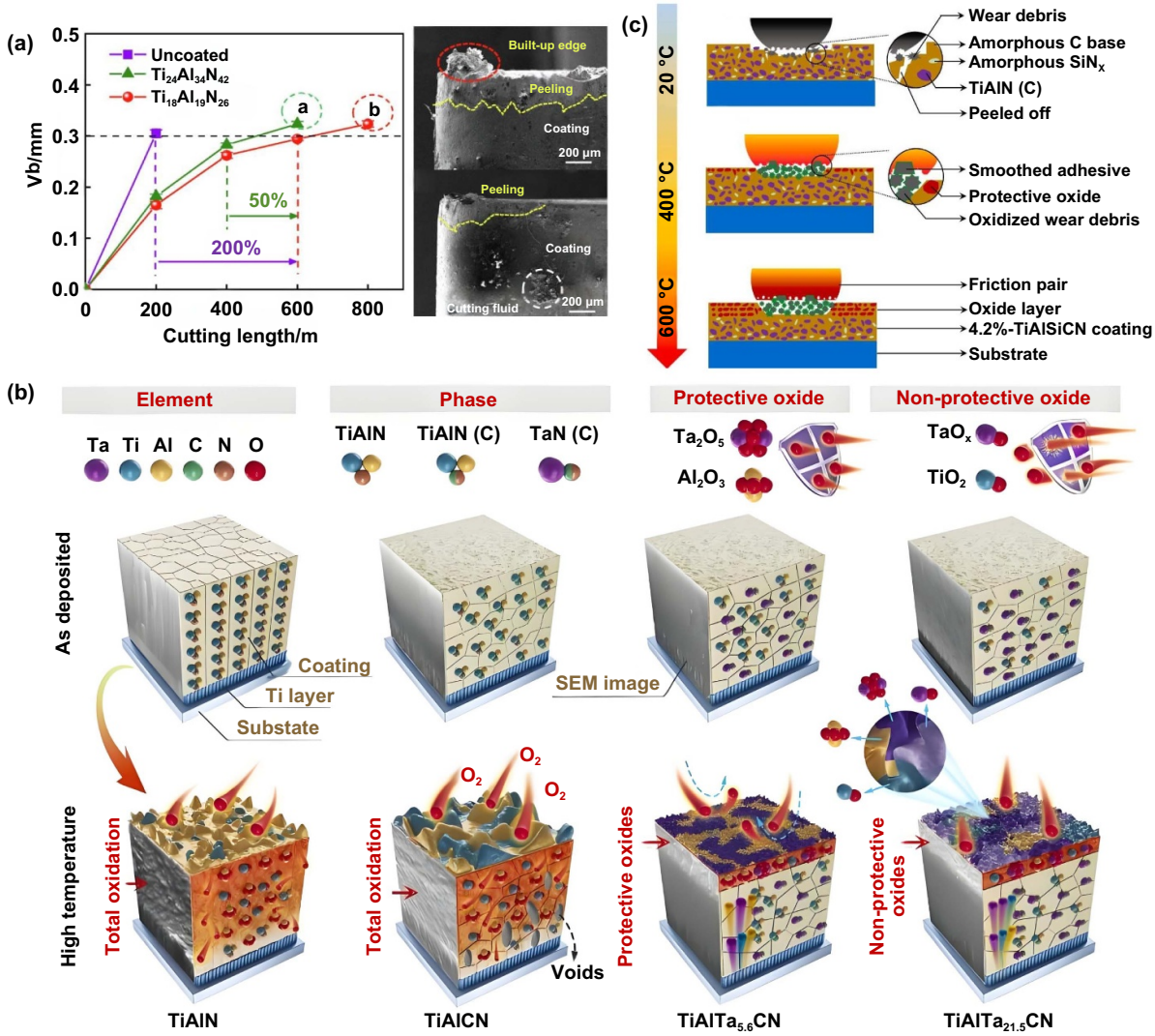


Figure 14. Cutting performance and adaptive mechanism of carbon-containing composite coating tools. (a) Flank wear (Vb) and the SEM images of $Ti_{24}Al_{34}N_{42}$ coated and $Ti_{18}Al_{19}C_{37}N_{26}$ coated tools in cutting the titanium alloy[155]. Reprinted from[155], Copyright (2022), with permission from Elsevier. (b) High temperature oxidation diagrams of TiAlN, TiAlCN, and TiAlTaCN coatings[156]. Reprinted from[156], Copyright (2024), with permission from Elsevier. (c) Wear behaviour schematic diagram of the 4.2%-TiAlSiCN after friction at different temperatures[157]. Reprinted from[157], Copyright © (2024), with permission from Elsevier.

In summary, the introduction of carbon into transition metal nitride coatings is an effective strategy for improving lubrication performance. However, the self-lubricating effect depends strongly on the form and content of carbon, as well as the operating temperature.

3.5. Soft metal composite coatings

Soft metals exhibit viscous flow and surface diffusivity at moderate temperatures, enabling the formation of lubricious surface films that reduce friction and wear[42,44]. A promising strategy for solid lubrication is based on self-adaptive mechanisms[50], where materials transform during use, generating low-friction tribo-oxides at the contact interface. Hybrid functional coatings that integrate oxidation-resistant matrices with noble metal lubricants provide optimized tribological performance[50,160]. Incorporating soft metal lubricants such as Ag, Pb, and Cu into hard coatings has proven effective in enhancing lubricity[161].

Silver (Ag) is the most commonly used soft metal solid lubricant, known for its excellent self-lubricating properties and its ability to lower the oxidation temperature of metals. TiAlN-Ag composite coatings demonstrate superior tribological properties compared to TiAlN coatings in both dry and lubricated environments[162]. Introducing an appropriate amount of Ag refines the grain structure and reduces internal stress, substantially improving the plasticity, hardness, and toughness of the coating. Furthermore, the solid lubrication provided by Ag significantly enhances the lubrication efficiency and wear characteristics of the composite coating[163]. MoVN is recognized as a promising material for high-temperature lubrication. Although Ag doping may decrease the mechanical strength of MoVN coatings, it enhances their tribological performance. Wang et al.[164]

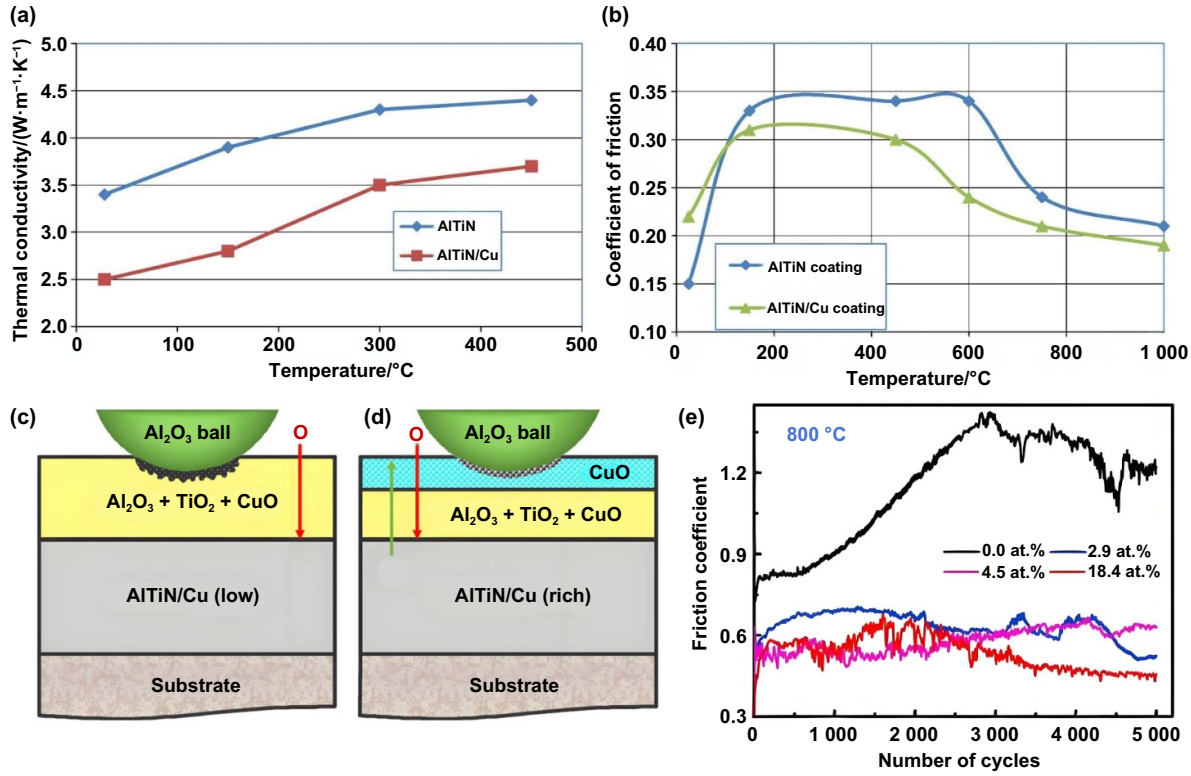


Figure 15. Properties and oxidation mechanism of AlTiN/Cu coating. (a) Thermal conductivity of AlTiN and AlTiN/Cu coatings as a function of temperature. (b) COF versus temperature data in contact with Inconel 718[161]. Reprinted from[161], Copyright (2010), with permission from Elsevier. (c) and (d) Oxidation-diffusion mechanism diagram of AlTiN/Cu coatings at 800 °C: (c) AlTiN/Cu (low Cu), (d) AlTiN/Cu (high Cu). (e) Friction curves of AlTiN/Cu coatings at 800 °C[167]. Reprinted from[167], Copyright © (2024), with permission from Elsevier.

developed a MoVN-Ag composite coating designed for lubrication across a broad temperature range. They found that a MoVN-Ag coating with 45.6 at.% Ag exhibits excellent self-lubricating properties, making it suitable for various temperatures. At 500 °C, Ag diffuses to the friction surface and forms a lubricating film. At 700 °C, Ag oxidizes to produce Ag_2MoO_4, a shear-prone phase, further forming a lubricating film[165]. At both 500 °C and 700 °C, MoVN-Ag composite coatings exhibited low friction coefficients of 0.19 and 0.28, respectively.

A main drawback of Al-rich TiAlN coatings is their lack of high-temperature lubricity, resulting in increased tool temperatures and friction, especially during high-speed dry cutting. Incorporating Cu into AlTiN to form AlTiN/Cu nanocomposite coatings markedly enhances their friction and wear performance. Previously, a multifunctional AlTiN/Cu nanomultilayer coated tool was reported, combining improved lubrication with decreased thermal conductivity, as shown in Figures 15(a) and (b)[161]. This design enables multiple energy dissipation pathways during frictional contact and substantially increases tool life under wear instability, as seen in machining Inconel 718 alloys. The tool life of the AlTiN/Cu coating is 2.3 times longer than that of the single-layer AlTiN coating. Chen et al.[166] prepared AlTiN-Cu, AlTiN/AlTiN-Cu, and AlTiN coatings on WC-6%Co substrates via cathodic arc evaporation and conducted milling tests on TC4 alloy under identical conditions. The addition of Cu lowered the hardness of AlTiN coatings but improved toughness. Therefore, the service lives of AlTiN-Cu and AlTiN/AlTiN-Cu coated tools increased by 11% and 24%, respectively, compared to AlTiN-coated tools.

In a recent study, Mei et al. examined the oxidation behavior and tribological properties of nano-multilayer AlTiN/Cu coatings[167]. The AlTiN/Cu coating containing 2.9 at.% Cu showed optimal wear resistance at room temperature, owing to the lubricating action of Cu and its oxide phase, CuO. However, at 800 °C, oxidation resistance declined and prominent oxidation stratification occurred. AlTiN/Cu coatings with low Cu content ($\leq$4.5 at.%) oxidized to form a composite oxide layer composed of CuO, TiO_2, and Al_2O_3, as depicted in Figure 15(c). Higher Cu content led to the formation of a double oxide layer due to outward diffusion and oxidation of Cu, with the top CuO layer contributing to a low friction coefficient of 0.53, as shown in Figures 15(d) and (e).

Nanocomposite coated cutting tools containing solid lubricants are increasingly recognized as promising for advanced machining. These coatings significantly enhance the cutting performance of challenging materials, such as titanium-based alloys used in aerospace applications. Notably, their performance is strongly influenced by structural design and the concentration of solid lubricants[168].

4. Discussion

4.1. Deposition methods of tool coatings

Compared with CVD, PVD technology has become the mainstream approach for cutting tool surface modification, due to its precise control of coating composition and structure, low-temperature processing, and environmental benefits[169]. The increasing use of hard-to-machine materials, stricter manufacturing cost controls, and higher environmental standards have driven the development and widespread adoption of PVD-coated cutting tools in recent years[170]. The main preparation methods for self-adaptive coated cutting tools discussed in this paper are summarized in Table 1.

Magnetron sputtering (MS) and arc ion plating (AIP) are the primary techniques for producing self-adaptive coated cutting tools. Magnetron sputtering can be further divided into direct current magnetron sputtering (DCMS), radio frequency magnetron sputtering (RFMS), and pulsed magnetron sputtering, depending on the power supply type[169]. Among these, high-power pulsed magnetron sputtering (HiPIMS) demonstrates significant advantages in improving the target ionization rate and enabling the preparation of high-performance coatings[172]. Filtered arc deposition (FAD) and ion-assisted deposition (IAD) technologies[173,174], which are both advancements derived from arc ion plating, are highly effective in eliminating droplet defects inherent to arc deposition. As PVD technology continues to evolve, hybrid PVD techniques have become important for depositing high-performance tool coatings[169]. Composite deposition harnesses the strengths of multiple processes, allowing a wider selection of compositions, easier regulation, and more effective control of internal stress[175–177]. Through the design of nano-multilayer and nanocomposite structures, and careful process optimization, coatings with superior properties can be fabricated, leading to significant improvements in tool cutting performance.

The deposition processes for soft coatings, hard coatings, and multi-architecture coatings display distinct characteristics. In the CrCN-WS_2 hard/soft coating system, the CrCN hard layer and WS_2 soft layer are deposited using different techniques[135]. The intermediate Cr layer and the CrCN hard coating are deposited by magnetron sputtering, while the WS_2 soft layer is applied onto the CrCN surface via electrohydrodynamic atomization (EHDA). In addition, nano-multilayer AlTiN/Cu coatings are fabricated with a hybrid system that combines AIP and pulsed DC magnetron sputtering (PDCMS), with the hard AlTiN layer and soft metallic Cu layer alternately deposited by AIP and PDCMS, respectively[167].

4.2. Self-adaptive coatings for cutting tools to match machining conditions

Modern manufacturing increasingly favors high-speed, efficient, precision, and eco-friendly cutting operations, leading to the adoption of advanced techniques such as high-speed cutting and dry/near-dry cutting in place of conventional methods[178,179]. These changes demand tool coatings with higher hardness, improved wear resistance, better oxidation resistance, and enhanced thermal stability. Table 2 summarizes the cutting conditions, performance requirements, and suitable coatings for high-speed, dry/near-dry, heavy-load. The frictional conditions associated with high temperature and high load are critical determinants of coated tool adaptability[90,180]. As discussed in Section 2.2, TiAlCrSiYN/TiAlCrN nano-multilayer coated cutting tools display excellent versatility and performance in the high-speed machining of Inconel 718 and other nickel-based superalloys. Yuan et al.[181] investigated the effect of initial high-speed cutting velocity on the machining of Ni-based high-temperature alloys with these adaptive nano-multilayer coated tools. The study found that higher cutting speeds during the initial stage accelerate the formation of multifunctional tribo-oxides on the tool surface. These tribo-oxides, composed primarily of Al_2O_3, $Al_6Si_2O_{13}$, TiO_2, TiO_x, and multivalent Cr oxides, work synergistically with chromium- and yttrium-based oxides to establish effective energy dissipation mechanisms at the interface, thereby significantly enhancing tribological performance during cutting[182,183].

Under typical cutting conditions, traditional coated cutting tools remain widely used. However, when machining difficult-to-cut materials—such as nickel or titanium alloys—cutting temperatures can exceed 1 000 °C, making standard coatings insufficient[14]. For hardened tool steels, coatings must combine improved oxidation resistance and high hot hardness to effectively manage wear. In aerospace alloys, elevated temperatures, high loads, and strong adhesive interactions lead to severe surface damage and unstable attrition wear, requiring coatings with a tailored set of properties[13,14]. The wear rates of coating materials at extremely high temperatures (>1 000 °C) are primarily determined by their chemical and mechanical properties[184]. Self-adaptive coated cutting tools offer superior chemical and mechanical performance under such extreme frictional conditions, representing a promising choice for advanced material machining.

Severe tool wear, chip adhesion, chipping, plastic deformation, and coating spalling are common during the machining of difficult materials with coated cutting tools[185]. Cutting tool wear can be classified as abrasive, adhesive, diffusive, or oxidative wear, depending on the underlying mechanisms[16,17,185]. Table 3 summarizes the deterioration mechanisms at different tool locations and the corresponding wear resistance mechanisms of coatings during the machining of various materials.

4.3. Advantages and limitations of self-adaptive coated cutting tools

Different coating materials and deposition methods result in varied cutting performance and tool life. Selecting coated cutting tools that match specific machining conditions can significantly enhance processing efficiency and extend tool durability. TiAlN is a widely used commercial tool coating recognized for its outstanding wear resistance and thermal stability.

Table 1. The preparation methods of self-adaptive coated cutting tools.

Deposition technologies	Coated cutting tools	References
Magnetron sputtering (MS)	TiAlN, TiAlCrN, TiAlSiVN, TiAlN/VN, TiAlN/WS, TiAlCN, TiAlTaCN, TiAlSiCN, TiAlN-Ag, MoVN-Ag	[53,75,85,97,155–157,162,164]
Arc ion plating (AIP)	TiAlCrSiYN, nano-multilayer TiAlCrSiYN/TiAlCrN, CrAlSiN	[88,89,106]
High power im-pulse magnetron sputtering (HiPIMS)	CrAlSiN	[171]
High power im-pulse magnetron sputtering and direct current magnetron sputtering hybrid PVD technology	TiAlCrN	[80]
Hollow cathode discharge and magnetron sputtering hybrid PVD technology	TiAlSiN	[20]
Arc ion plating and mid-frequency magnetron sputtering hybrid PVD technology	TiAlSiN	[52]
Mid-frequency magnetron sputtering and ion beam-assisted hybrid PVD technology	WS_2	[125,126]
Unfiltered cathodic arc system; RF magnetron sputtering	DLC	[147,148]
Magnetron sputtering + electro-hydrodynamic atomization technology (EHDA)	CrCN-WS_2 hard-soft coating	[135]
Cathode arc evaporation	AlTiN-Cu	[166]
Arc ion plating and pulsed DC magnetron sputtering (PDCMS) hybrid PVD technology	Nano-multilayer AlTiN/Cu	[167]

Table 2. Different cutting conditions and applicable tool coatings.

Cutting conditions	Cutting characteristics	Tool performance requirements (in priority order)	Applicable coated tools	Tribological properties of coatings	Machining materials
High-speed	Enhanced friction and oxidation, significant local temperature rise	1. Oxidation resistance 2. Hot-hardening stability 3. Low COF 4. Self-lubrication 5. Anti-adhesion	AlTiN, TiAlN, TiAlCrN, TiAlSiN, CrAlSiN, TiAlCN, TiAlCrSiYN, TiAlCrSiYN/TiAlCrN, TiAlN/WS, TiAlSiCN, TiAlTaCN	Dense low-friction oxide film or self-lubricating phase formed in situ at high temperature stabilizes the interface	Titanium alloy, nickel-based alloy, stainless steel, superalloy, ceramic matrix composites
Dry/near-dry	Friction and temperature rise, limited lubrication, chip removal difficulties	1. Self-lubrication 2. Wear resistance 3. Oxidation resistance 4. Anti-adhesion 5. Thermal stability	AlTiN, TiAlN, TiSiVN TiAlSiVN, TiAlN/VN, CrCN-WS_2, TiAlN/WS TiAlCrSiN, DLC, WS_2, AlTiN/Cu	Low and stable COF maintained by self-generated oxide films or solid lubricating phase	Titanium alloy, stainless steel, aviation and automotive parts
Heavy-load	Large cutting force, high cutting temperature, high mechanical load	1. Hardness 2. Toughness 3. Abrasion resistance 4. Adhesion 5. Anti-fatigue	AlTiN, TiAlN, TiAlCrN, TiAlSiN, CrAlSiN, TiAlCN	Maintain wear resistance and lubrication at medium/high temperatures, enhance toughness	Die steel, high-hardness alloy, cast iron, other high-strength materials

Table 3. Main deterioration mechanisms of different parts of the cutting tool during machining of various materials and the wear resistance mechanisms of coatings.

Parts of the cutting tool	Main deterioration mechanisms during machining different materials[186–190]	Wear resistance mechanisms of coatings
Nose radius	(1) Thermal fatigue, plastic deformation (2) Chipping, diffusion wear (3) Chipping, plastic deformation (4) Abrasive wear, chipping	1) Al increases hot hardness, mitigates thermal softening 2) Cr and Ta improve toughness, reduce chipping 3) Si enhances hardness, suppresses crack propagation 4) V, Mo, C, WS_2, DLC, Cu, and Ag provide self-lubrication, alleviate plastic deformation
Rake face	(1) Adhesive wear, oxidation wear, diffusion wear (2) Diffusion wear, adhesive wear (3) Adhesive wear, abrasive wear (4) Abrasive wear, diffusion wear	1) Al, Cr, Si, and Ta improve oxidation resistance, thermal barrier protection 2) Si increases hardness, suppresses crack growth 3) V, Mo, C, WS_2, DLC, Cu, and Ag provide self-lubrication, reduce forces, and minimize adhesion 4) Cr, Si, and Y refine grains, inhibit crack initiation
Flank face	(1) Adhesive wear, oxidation wear, diffusion wear (2) Adhesive wear, abrasive wear (3) Adhesive wear, abrasive wear (4) Abrasive wear	1) Al, Cr, and Si ensure high hardness, delay wear land growth, and enhance resistance 2) V, Mo, C, WS_2, DLC, Cu, and Ag provide self-lubrication, reduce forces, minimize adhesion

Note: different materials: (1) high-temperature alloys; (2) stainless steel;(3) aluminum and copper alloys; (4) carbon steel and cast iron.

However, it is limited by a relatively high COF and inadequate high-temperature lubricity. Incorporating alloying elements such as Cr, Si, Y, B, and Ta can further improve the hardness, oxidation resistance, and thermal stability of TiAlN coatings. In addition, incorporating elements such as V, Mo, W, or soft metals like Ag and Cu can enhance lubricating performance at medium to high temperatures. However, doping with these elements can also introduce trade-offs in performance. For example, TiAlSiN coatings display higher hardness and wear resistance than TiAlN coatings but tend to exhibit increased friction coefficients and lower adhesion strength[191,192]. TiAlCrN and TiAlTaN coatings show improved oxidation resistance but reduced toughness and plasticity[193]. The oxidation resistance of TiAlVN and TiAlMoN coatings can be compromised[194]. Furthermore, the hardness of composite coatings containing carbon or soft metals declines as the content of these components increases. The properties and machinability of tool coatings can be further optimized through nano-structural design. Nano-multilayer and nanocomposite structures are now widely employed in the development of advanced tool coatings. Compared with conventional TiAlN coatings, most TiAlN-based nanocomposite and nano-multilayer coatings exhibit marked improvements in hardness, high-temperature lubricity, and oxidation resistance. Therefore, the tool life when processing difficult-to-cut materials can often be extended by one to two times. Table 4 presents a comparison of tool life for different coated tools relative to commercial TiAlN-coated tools under identical cutting conditions.

Although soft-coated cutting tools with self-lubricating features can provide good lubrication, there are still several limitations in practical applications. First, the COF of soft coatings may increase during prolonged use. Second, compared to hard coatings, soft coatings generally have lower wear resistance and are more likely to wear out under high load or demanding machining conditions, which reduces tool life. Third, some soft coatings may be unstable in specific chemical environments and are susceptible to corrosion. Fourth, at high temperatures, some soft coatings may lose their lubricating function. Therefore, soft-coated cutting tools are best suited for specialized applications, such as low speeds, light loads, or tasks requiring high surface quality. In practice, soft coatings are often combined with hard coatings. Soft-hard composite coatings improve abrasion resistance, although they may have reduced hardness and adhesion. In contrast, TiAlN/WS self-lubricating nanocoatings with multilayered architecture successfully combine the low COF of WS_2 with the wear resistance of TiAlN, achieving high adhesion and stable hardness. This nano-multilayer design provides a new direction for the development of soft coatings.

To facilitate a comprehensive comparison of different coating materials, the results are summarized in Table 5.

Table 4. Comparison of cutting force, temperature, and tool life between different coated cutting tools and TiAlN-coated tools under the same cutting conditions.

Coated tools	Deposition methods	Machining materials	Process parameters	Cutting force	Temperature	Tool life changes	References
TiAlN	—	—	—	+ +	+ + +	100%	—
TiAlCrN	Arc ion plating (AIP)	Hardened tool steel H13	Dry milling; $V_c = 200$ m·min^{-1}, $f_z = 840$ mm·min^{-1}, $a_p = 5$ mm	+ + +	+ + + +	127%; 200%	[13] [195]
TiAlSiN; Gradient TiAlSiN	Magnetron sputtering (MS)	TC4 titanium alloys	Wet turning; $V_c = 100$ m·min^{-1}, $f_z = 0.2$ mm·rev^{-1}, $a_p = 0.5$ mm	+ + + + + +	+ + + + + + + +	200% 350%	[191] [191]
TiAlSiN CrAlSiN	Cathodic arc evaporation (CAE)	Ti-6Al-4 V alloys	Dry milling; $V_c = 350$ m·min^{-1}, $f_z = 0.02$ mm·tooth^{-1}, $a_p = 0.3$ mm	+ + + + + + +	+ + + + + + + +	125% 420%	[196] [196]
TiAlCrSiYN TiAlCrSiYN/ TiAlCrN	Arc ion plating (AIP)	Inconel 718 alloys	Turning; $V_c = 40$ m·min^{-1}, $f_z = 0.125$ mm·rev^{-1}, $a_p = 0.25$ mm	+ + + + + + + +	+ + + + + + + +	195% 258%	[89] [89]
DLC	RF magnetron sputtering	Ti-6Al-4 V alloys	Dry micro-milling; $V_c = 9.6$ m·min^{-1}, $f_z = 0.1$ μm·tooth^{-1}, $a_p = 10$ μm	+ + + + +	+ +	640%	[146]
TiAlN/VN	CAE and unbalanced MS	Ti-6Al-4 V alloys	Turning; $V_c = 150$ m·min^{-1}, $f_z = 0.125$ mm·rev^{-1}, $a_p = 0.25$ mm	+ + + +	+ + +	150%	[44]
TiAlN/WS	Magnetron sputtering	TC4 titanium alloy	Turning; $V_c = 100$ m·min^{-1}, $f_z = 950$ mm·min^{-1}, $a_p = 0.3$ mm	+ + + +	+ + +	200%	[53]
TiAlCN	Me-dium frequency MS	TC4 titanium alloy	Turning; $V_c = 100$ m·min^{-1}, $f_z = 0.2$ mm·rev^{-1}, $a_p = 0.5$ mm	+ + +	+ + + +	150%	[155]
TiAlTaCN	Reactive MS	TC4 titanium alloy	Turning; $V_c = 100$ m·min^{-1}, $f_z = 0.2$ mm·rev^{-1}, $a_p = 0.5$ mm	+ + + +	+ + + + +	300%	[156]
TiAlSiCN	Reactive MS	TC4 titanium alloy	Turning; $V_c = 100$ m·min^{-1}, $f_z = 0.2$ mm·rev^{-1}, $a_p = 0.5$ mm	+ + + +	+ + + + +	225%	[157]
AlTiN-Cu	Cathode arc evaporation	TC4 titanium alloy	Wet milling; $V_c = 60$ m·min^{-1}, $f_z = 0.15$ mm·rev^{-1}, $a_p = 1.5$ mm	+ + + +	+ + +	111%	[166]
Nanomultilayered AlTiN/Cu	Unbalanced MS	Inconel 718	Turning; $V_c = 40$ m·min^{-1}, $f_z = 0.125$ mm·rev^{-1}, $a_p = 0.25$ mm	+ + + +	+ + + +	230%	[161]

"+": the positive change of cutting force and cutting temperature

Table 5. Comparison of performance parameters of different self-adaptive coated cutting tools.

	Tool coatings	Hardness/GPa	Adhesion/N	Oxidation temperature/°C	COF	Tribo-films or lubricating films	References
Self-organizing coatings	TiAlN	28−40	50−80	<850	0.6−0.8	Al2O3	[73–75,197]
	TiAlCrN	20−40	75−100	>1 000	0.4−0.6	Al2O3, Cr2O3	[13,80,85,198]
	TiAlSiN	30−42	21−29	>1 000	0.36−0.64	Al2O3, SiO2	[52,192]
	TiAlVN	40−50	—	>600	0.35−0.45	Al2O3, V2O5	[93]
	TiAlSiVN	28−34	60 ± 2	>900	0.5−0.6	Al2O3, V2O5, SiO2	[96]
	TiAlCrSiYN	29.9	—	>900	0.15 (at 1 200 °C)	Al-O, Si-O,Cr-O, Y-O	[88]
	TiAlCrSiYN/ TiAlCrN	28−34	—	>900	0.15−0.2 (at 1 000 °C)	Al2O3, Al2Si2O3, Si-O, Cr-O, Y-O	[89]
	TiAlN/VN	31.4 ± 2.6	46.8 ± 2.1	<800	0.2−0.3 (at 700 °C)	Al2O3, V2O5	[97]
	AlTiN/MoN	26.13	—	<850	0.2 (at 1 000 °C)	Al2O3, MoO3	[44]
	CrAlSiN	33−55	50	>900	0.3−0.5	Al2O3, Cr2O3, SiO2	[106,171]
Self-lubricating coatings	WS2	515.4 (Hv)	43.25	<400	0.05−0.2	WS2	[125]
	WS2/Zr	6.5	42	—	0.4−0.5	WS2	[131]
	MoS2/Y	7.5 ± 0.4	50	—	0.128	MoS2	[133]
	DLC	16−25	12−25	<600	0.14−0.16	DLC	[148]
	CrCN-WS2	—	52	—	0.6	Cr2O3, WS2	[135]
	TiAlN/WS	14.25	135.4	—	0.261	WS, Al2O3	[53]
	TiAlCN	20.36	156	—	0.231	Al2O3, amorphous C	[155]
	TiAlTaCN	23.77	162	>1 000	0.28	Al2O3, Ta2O5, TaN, amorphous C	[156]
	TiAlSiCN	25.24	153	—	0.24	SiNx, amorphous C	[157]
	TiAlN-Ag	12−28	68.61	<800	0.3−0.4	Ag, Al2O3	[162]
	MoVN-Ag	2.1−4.4	—	<700	0.19−0.23 (at 500 °C)	Ag, MoO3, Ag2MoO4	[164]
	AlTiN/Cu	14−29	—	<850	0.53	Cu, CuO, Al2O3, TiO2	[167]

Hardness, wear resistance, oxidation resistance, and lubricity are critical parameters for evaluating tool coating performance. Each coating material presents its own combination of strengths and limitations. Therefore, the selection of tool coatings should be based on a comprehensive evaluation of both the cutting conditions and the workpiece properties. By considering these factors, the optimal coating material can be identified to maximize tool performance and efficiency.

5. Summary and outlook

Self-adaptive coated cutting tools have received increasing attention in recent years, and many new approaches and concepts have been proposed to advance their development. This review summarizes recent progress in self-adaptive coated cutting tools, with a focus on both self-organizing and self-lubricating systems. Hard-coated cutting tools with self-organizing functions remain the most widely studied and have already achieved some commercial applications. TiAlN and DLC coating technologies are well-established and widely used as commercial coatings for cutting tools. In practical industrial applications, TiAlN-coated tools are mainly used in high-speed machining and dry cutting of hardened steels and superalloys, while DLC-coated tools are commonly applied to the machining of non-ferrous alloys, polymers, and composite materials. TiAlSiN and AlCrSiN coatings have achieved limited commercialization and are primarily used in many specific machining scenarios, such as for aerospace components and turbine blades. Soft-coated tools offer excellent lubricating performance, but their applicable temperature range is limited. Composite coatings with self-lubricating properties often show improved adaptability and are suitable for high-temperature machining, but they remain largely confined to laboratory-scale research.

Although self-adaptive coatings show great potential in performance, their transition from laboratory research to large-scale industrialization faces challenges. First, fabrication relies on advanced deposition techniques and complex processes, increasing production costs and cycle times. Second, achieving self-adaptive properties requires precise control over chemistry and microstructure, making the process highly sensitive to fluctuations and hindering consistency and batch uniformity in mass production. For example, although Me-Si-N-based nanocomposite coatings exhibit excellent hardness and thermal stability, their process repeatability and consistency in large-scale fabrication remain challenging. Third, the current market demand for self-adaptive coated cutting tools is relatively low. In most conventional machining scenarios (such as general steels and cast iron), mature coatings like TiN, TiAlN, and AlCrN can already meet the requirements. Self-adaptive coatings are mainly used for difficult-to-machine materials or under extreme cutting conditions in specific sectors such as aerospace and energy equipment. This

narrow application scope constrains market scale and reduces economic incentives for manufacturers to invest in large-scale production and process optimization. Therefore, considerable technical challenges must be addressed to transition these coatings from laboratory demonstrations to widespread commercial application.

Based on current research, the following potential future directions are highlighted:

(1) While self-adaptive coated cutting tools have shown progress in improving high-temperature lubrication and wear resistance, achieving a perfect balance between these properties remains challenging. Further research should focus on developing multifunctional coatings that provide not only excellent cutting performance at elevated temperatures and pressures, but also additional functions such as corrosion resistance and vibration reduction.
(2) Self-adaptive coatings often require precise multilayered, composite nanostructures, or gradient compositions, placing stringent demands on deposition techniques such as PVD and hybrid PVD. Future work should focus on developing new deposition technologies and optimizing processes, while also incorporating sustainability considerations—such as reducing energy consumption, improving resource efficiency, and minimizing hazardous by-products—to advance green manufacturing.
(3) Future efforts should combine material simulation and experimental validation to explore new coating structures and properties, providing momentum for further advancement. In particular, with the rapid development of artificial intelligence in materials science, data-driven modeling and intelligent prediction are becoming powerful tools for accelerating the discovery and optimization of self-adaptive coatings. Integrating AI with high-throughput simulations and experimental databases may significantly shorten the development cycle, guide the design of advanced coating architectures, and enhance the synergy between academic research and industrial application.
(4) Exploring the synergistic mechanisms between self-adaptive coatings and emerging manufacturing technologies—for example, utilizing additive manufacturing to achieve integrated structural-functional design and precise forming of coatings, and combining hybrid machining to optimize interfacial bonding and service performance—can provide new technological pathways for the development of next-generation high-performance coated cutting tools.
(5) Future advances should emphasize integration with artificial intelligence and IoT technologies. By incorporating sensors and intelligent controllers, real-time monitoring and control of coated tools can be achieved, improving stability and processing efficiency.
(6) It is crucial to establish and revise relevant standards, such as those for performance evaluation, preparation processes, and environmental adaptability. Improving the standards for self-adaptive coatings can ensure their quality, performance, environmental compatibility, and safety.

This will boost the development and application of self-adaptive coating technologies and support the sustainable growth of the coatings industry.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Nos. 52275428, 52475498), the Major Project on the Integration of Industry and Research of Fujian Province (No. 2024H6011), and Xiamen Science and Technology Major Project (No. 3502Z20231009).

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