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# Research progress and applications of high-power pulsed magnetron sputtering technology and its hybrid techniques

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## Abstract

High-power pulsed magnetron sputtering is a novel, advanced physical vapor deposition (PVD) technique. With advantages such as high sputtering ionization rates, dense and uniform coatings, and strong substrate-coating adhesion, it shows great promise for applications in the field of cutting tool coatings. This paper outlines the basic principles and core advantages of high-power pulsed magnetron sputtering technology and systematically analyzes the challenges encountered in industrial applications, including low deposition rates, insufficient ionization of certain target materials, and high coating stress. This paper focuses on reviewing the hybrid forms of high-power pulsed magnetron sputtering combined with direct-current magnetron sputtering, radio-frequency magnetron sputtering, medium-frequency magnetron sputtering, and arc ion plating, elucidating the synergistic mechanisms and performance enhancement effects of these hybrid technologies. Focusing on tool coatings, this paper provides a detailed introduction to the current applications of high-power pulsed magnetron sputtering and its hybrid technologies in the preparation of hard coatings and wear-resistant coatings, and analyzes their role in improving the cutting performance and service life of cutting tools. Finally, the paper summarizes the shortcomings in current technological development and outlines future research directions and prospects for industrial applications.

**Keywords:** HiPIMS; Hybrid technology; Tool coatings; Hard coatings; Deposition rate

## 1. Introduction

Tool coating technology is a key method for enhancing tool performance and extending service life, and it plays a crucial role in improving the efficiency of modern machining. Physical vapor deposition (PVD) technology has become the mainstream method for tool coating preparation due to its advantages, such as high coating quality and environmental friendliness. High-power pulsed magnetron sputtering technology, as a major innovation in the field of physical vapor deposition, utilizes a pulsed power supply with high peak power and low duty cycle to generate high-energy-density plasma on the target surface. This significantly increases the ionization rate of sputtered particles, thereby addressing the shortcomings of traditional magnetron sputtering, such as low film density and poor adhesion[1].

Since the advent of high-power pulsed magnetron sputtering technology, research into its application in tool coating has continued to deepen. It can produce various coatings with high hardness, excellent wear resistance, and strong corrosion resistance, effectively improving the service performance of cutting tools under severe conditions such as high-speed cutting and dry cutting. However, standalone high-power pulsed magnetron sputtering technology suffers from low deposition rates and relatively high process costs, limiting its large-scale industrial application[2]. To leverage its technical advantages and mitigate its inherent limitations, researchers have combined high-power pulsed magnetron sputtering with other physical vapor deposition (PVD) techniques to develop various highly efficient hybrid coating

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technologies. These innovations not only increase deposition rates but also further optimize coating performance, thereby accelerating the industrialization of this technology in the field of cutting tool coatings. This paper reviews the research progress and current applications of high-power pulsed magnetron sputtering technology and its hybrid techniques in the context of cutting tool coating research, and provides an outlook on future trends to serve as a reference for related research and engineering applications.

## 2. Key Features and Limitations of High-Power Pulsed Magnetron Sputtering Technology

### 2.1. Key Features

The core advantage of high-power pulsed magnetron sputtering technology stems from its unique pulsed discharge mode; compared to conventional DC magnetron sputtering, it offers significant advantages in terms of plasma characteristics and film quality[3]. This technology employs a high-peak-power pulsed power supply, with a peak power density that can reach tens or even hundreds of times that of conventional DC magnetron sputtering. This generates a high-density plasma on the target surface, significantly increasing the ionization rate of sputtered atoms—typically exceeding 80%, far higher than the less than 10% achieved by conventional DC magnetron sputtering.

The high ionization rate enables sputtered particles to deposit more uniformly on the substrate surface, effectively eliminating the directionality defects associated with conventional magnetron sputtering, and allowing for the preparation of coatings with uniform thickness and dense structure on the surfaces of complex-shaped cutting tools[4]. At the same time, high-energy ions bombarding the substrate surface can remove contaminants from the substrate surface, enhance the adhesion at the film-substrate interface, and prevent coating peeling. Furthermore, coatings prepared using high-power pulsed magnetron sputtering technology exhibit excellent mechanical properties. The hardness of the hard coatings can reach over 30GPa, and their resistance to friction and wear is significantly superior to that of conventional coatings, meeting the operational requirements of cutting tools under severe conditions such as high-speed and heavy-load machining.

In the preparation of cutting tool coatings, high-power pulsed magnetron sputtering technology can flexibly accommodate a variety of target materials, including metal targets such as titanium, aluminum, and chromium, as well as related compound targets. It can produce common cutting tool hard coatings such as TiAlN, CrN, and TiN, among other commonly used hard coatings for cutting tools. Furthermore, the composition and structure of the coatings can be precisely controlled by adjusting process parameters to meet the requirements of different tool types and cutting conditions.

### 2.2. Existing Shortcomings

Although high-power pulsed magnetron sputtering technology offers significant advantages in the preparation of tool coatings, from the perspective of industrial application, there are still some issues that urgently need to be addressed. Among these, low deposition rates represent the core bottleneck limiting its large-scale adoption. Since high-power pulsed magnetron sputtering employs a low-duty-cycle pulsed power supply, the sputtering time of the target material is short, and some highly ionized sputtering ions are re-absorbed by the cathode target surface. This results in a reduced number of effective sputtering particles reaching the substrate surface, leading to a deposition rate significantly lower than that of conventional DC magnetron sputtering technology[5].

Studies have shown that when using a titanium target to prepare coatings, the deposition rate of high-power pulsed magnetron sputtering is only about 30% of that of conventional DC magnetron sputtering; even when using easily sputtered target materials such as copper and silver, the deposition rate is only 60% to 85% of that of conventional technology[6]. For the industrial production of tool coatings, low deposition rates lead to reduced production efficiency and increased production costs, making it difficult to meet the demands of large-scale batch production.

Furthermore, for metal targets with low sputtering rates, such as titanium and vanadium, the particle ionization rate of high-power pulsed magnetron sputtering systems still has room for improvement, hindering further optimization of coating performance. At the same time, the high cost of the pulse power supply, the complexity of process parameter control, and the demanding requirements for equipment operation and maintenance also limit its industrial application to some extent.

## 3. Recent Advances in High-Power Pulsed Magnetron Sputtering Hybrid Technology

To address the shortcomings of high-power pulsed magnetron sputtering technology, researchers have combined it with other physical vapor deposition (PVD) techniques to leverage their complementary strengths. This approach not only enhances deposition rates and optimizes coating performance but also reduces process complexity and production costs. Currently, high-power pulsed magnetron sputtering hybrid technologies are primarily divided into two categories: one involves combining with other magnetron sputtering techniques, and the other involves combining with other physical vapor deposition (PVD) techniques such as arc ion plating. Each type of hybrid technology has demonstrated excellent performance in the preparation of cutting tool coatings.

### 3.1. Combination with Other Magnetron Sputtering Techniques

#### *3.1.1. Combination with DC Magnetron Sputtering*

DC magnetron sputtering technology offers advantages such as high deposition rates, low equipment costs, and process stability. Combining it with high-power pulsed magnetron sputtering allows the two technologies to complement each other's strengths, resulting in a hybrid DC magnetron sputtering–high-power pulsed magnetron sputtering technology. In this hybrid technology, DC magnetron sputtering provides a high deposition rate[7], while high-power pulsed magnetron sputtering leverages its high ionization rate to optimize coating structure and performance, achieving a balance between deposition rate and coating quality.

In the preparation of tool coatings, this hybrid technology can effectively improve the deposition efficiency and performance of hard coatings such as TiN and TiAlN. Research has shown that a hybrid power supply consisting of one high-power pulsed magnetron sputtering power source and three DC magnetron sputtering power sources, as shown in Figure 1, The deposition rate of the prepared TiN coating was significantly improved compared to single DC magnetron sputtering technology. At the same time, the residual compressive stress of the coating was significantly reduced, the microhardness increased from 34.8GPa to 38.0GPa, and the adhesion between the coating and the substrate was greatly enhanced, effectively extending the service life of the cutting tools[8].

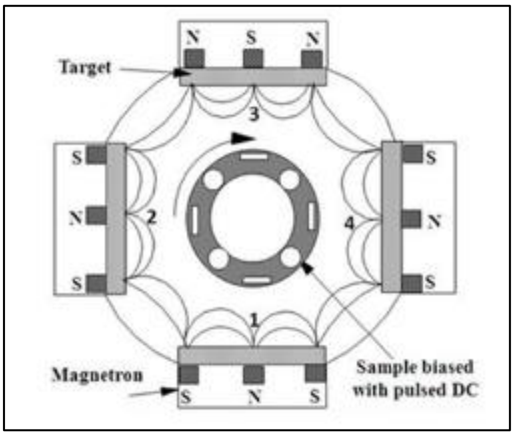

**Figure 1** Schematic diagram of the four Ti targets closed field unbalanced magnetron sputtering ion plating system: one target is connected to a HIPIMS power supply and the other three operated in a conventional DC-Magnetron mode[8]

Furthermore, the pre-ionization effect of DC magnetron sputtering improves the discharge stability of high-power pulsed magnetron sputtering at low pressures, reduces discharge delay, and enables the hybrid technology to operate stably at lower pressures, thereby further optimizing coating density. This composite technology has been widely applied in the preparation of coatings for high-speed steel and cemented carbide cutting tools. It enhances cutting performance while reducing production costs, making it suitable for industrial-scale batch production.

#### *3.1.2. Combination with RF Magnetron Sputtering*

The advantages of RF magnetron sputtering technology lie in its wide range of compatible sputtering targets, the ability to simultaneously sputter both metallic and insulating targets, and its high sputtering rate. Combining this with high-power pulsed magnetron sputtering to form an RF magnetron sputtering–high-power pulsed magnetron sputtering hybrid technology expands the range of target materials available for tool coatings, while simultaneously enhancing coating performance.

This hybrid technology offers significant advantages in the preparation of functional coatings for cutting tools, such as oxides and nitrides. As shown in Figure 2, NbSi coatings prepared using a hybrid method combining high-power pulsed magnetron sputtering with a niobium target and RF magnetron sputtering with a silicon target can operate stably at lower pressures, exhibit high deposition rates, and possess excellent superconducting properties and resistivity, making them suitable for the preparation of functional coatings for high-end cutting tools[9]. Furthermore, this hybrid technique effectively addresses the issues of arcing and deposition instability commonly encountered in high-power pulsed magnetron sputtering of insulating targets, thereby expanding the variety and application scope of tool coatings.

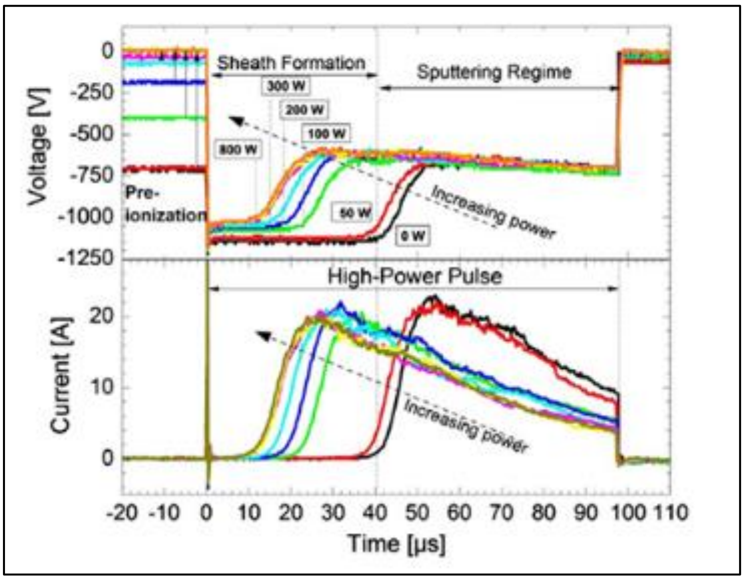

**Figure 2** Voltage (top panel) and current (bottom panel) pulse waveforms recorded for co sputtering hybrid RF/HiPIMS process in respect of RF power at 0.1Pa and 140W average HiPIMS power.The dashedarrowsindicate therisingofthe RF power, and solid (vertical) arrows the DC pre-ionization bias established before the pulse[9]

It should be noted that RF magnetron sputtering power supplies consume a significant amount of energy and pose certain health risks to humans. In industrial applications, power supply designs must be optimized to reduce energy consumption and safety risks, thereby further promoting the adoption of this hybrid technology in the field of cutting tool coatings.

### *3.1.3. Combination with Medium-Frequency Magnetron Sputtering*

Medium-frequency magnetron sputtering technology employs a twin-target alternating operation mode, which effectively suppresses arc discharge and surface poisoning of the target material. It is suitable for the preparation of composite coatings and offers a high deposition rate. Combining this with high-power pulsed magnetron sputtering to form a medium-frequency magnetron sputtering–high-power pulsed magnetron sputtering hybrid technique can further enhance coating deposition efficiency and performance, suppress arcing, and is suitable for the preparation of tool coatings under reactive atmospheres.

This hybrid technique is widely used in the preparation of oxide tool coatings such as $TiO_2$ and $Al_2O_3$. As shown in Figure 3, studies have demonstrated that, compared to single high-power pulsed magnetron sputtering technology, $TiO_2$ coatings prepared using the medium-frequency magnetron sputtering–high-power pulsed magnetron sputtering hybrid technique exhibit superior crystallinity, fewer defects, and better thermal stability and electrochemical performance, effectively enhancing the corrosion resistance and high-temperature stability of cutting tools[10]. In the preparation of $Al_2O_3$ coatings, this hybrid technique can significantly increase the deposition rate while reducing internal compressive stress in the coating, thereby preventing cracking and improving the coating’s wear resistance and service life[11].

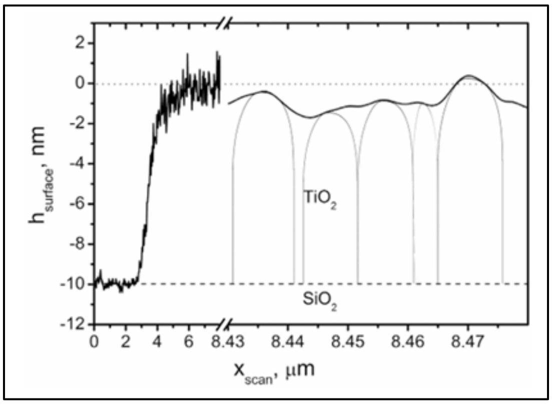

**Figure 3** The height variation along the SPM line scan in a sample with the step-like edge of the as-grown $TiO_2$ film deposited at 650K. The $SiO_2$ is the surface plane of the substrate[11]

Furthermore, by adjusting the power supply configuration and process parameters, this hybrid technique enables precise control over coating structure and performance, adapting to the requirements of different types of cutting tools, and offers significant advantages in the preparation of coatings for complex-shaped cutting tools.

### 3.2. Combination with Arc Ion Plating Technology

Arc ion plating technology offers advantages such as high ionization efficiency and fast deposition rates; however, the deposition process generates a large number of metal droplets, resulting in high surface roughness of the coating. This affects the cutting accuracy of the tool and limits its application in the preparation of coatings for high-end cutting tools. Combining high-power pulsed magnetron sputtering with arc ion plating to form an arc ion plating–high-power pulsed magnetron sputtering hybrid technology allows for the integration of both techniques' strengths, thereby improving coating surface quality and enhancing coating performance.

In this hybrid technique, arc ion plating provides a high deposition rate, while high-power pulsed magnetron sputtering leverages its high ionization rate and low surface roughness to modify the coating surface, reduce metal droplets and surface defects, and refine the coating grain size, thereby enhancing the coating's hardness and wear resistance. For example, TiN coatings prepared using a combination of cathodic arc evaporation and high-power pulsed magnetron sputtering exhibit a significant reduction in the number and size of macroscopic particles on the coating surface compared to coatings produced by arc ion plating alone. The grain size is refined from 121nm to 47.8nm, and both hardness and adhesion to the substrate are substantially improved, effectively enhancing the cutting accuracy and service life of cutting tools[12].

In the preparation of high-end tool hard coatings such as AlCrN and Cr-Mo-Si-N, this hybrid technology effectively enhances the ionization of gas and metal, forming dense nano-composite structure coatings with a maximum hardness of up to 26.5GPa. Their oxidation resistance and wear resistance are significantly superior to those of coatings prepared using single-technique methods[13, 14]. Furthermore, by regulating the oxygen supply method, this composite technology can suppress arc discharge in high-power pulsed magnetron sputtering sources, thereby further improving coating quality and making it suitable for the preparation of coatings for high-end precision cutting tools.

## 4. Applications of High-Power Pulsed Magnetron Sputtering and Its Hybrid Technologies in Tool Coatings

High-power pulsed magnetron sputtering and its composite technologies are widely used in the field of cutting tool coatings due to their excellent coating preparation capabilities. They can produce various types of coatings, including hard coatings, wear-resistant coatings, and lubricating coatings, suitable for tools made of high-speed steel, cemented carbide, ceramics, effectively enhancing tool performance under demanding conditions such as high-speed cutting, dry cutting, and heavy-duty cutting, thereby extending tool life and reducing machining costs.

### 4.1. Applications in the Preparation of Hard Coatings

Hard coatings are the predominant type of coating for cutting tools, primarily used to enhance tool hardness and wear resistance, thereby extending the service life of the tools during the cutting process. High-power pulsed magnetron sputtering technology can be used to prepare various high-performance hard coatings, such as TiAlN, CrN, and TiCN. Its high ionization rate results in dense coating structures with strong substrate adhesion, and hardness levels exceeding 30GPa, enabling effective resistance to wear and impact during the cutting process[15].

TiAlN coatings prepared using high-power pulsed magnetron sputtering technology exhibit excellent high-temperature stability and oxidation resistance, enabling them to operate stably at temperatures above 800°C and making them suitable for high-speed and dry cutting conditions[16]. Experimental data indicate that when this coating was applied to a cemented carbide milling cutter, under conditions of machining 45 steel at a cutting speed of 120m/min and a feed rate of 0.2mm/r, the wear on the tool's rake face decreased from 0.32mm for the uncoated tool to 0.11mm, a reduction of 65.6%. and tool life increased from 80 minutes to 250 minutes, a 212.5% improvement. In the preparation of coatings for high-speed steel drill bits, CrN coatings produced via high-power pulsed magnetron sputtering were tested and found to increase the drill bit hardness from 65 HRC to 88 HRC. Under conditions of an 8 mm drill diameter and a rotational speed of 1,500 rpm, the number of holes drilled per drill bit increased from 230 to 780, with the wear rate reduced by 70.5%. drilling efficiency increased by 35%, and the surface roughness of the drilled holes decreased from Ra 1.2μm to Ra 0.35μm[17, 18].

High-power pulsed magnetron sputtering hybrid technology further optimizes the performance of hard coatings. As shown in Figure 4, TiAlSiN coatings prepared using DC magnetron sputtering–high-power pulsed magnetron sputtering hybrid technology can achieve a hardness of up to 34.1GPa, a coefficient of friction as low as 0.46, and a wear rate of $2.1\times10^{-6}$ mm$^3$·N$^{-1}$·m$^{-1}$ under dry friction conditions at room temperature—a 68% reduction compared to coatings prepared by DC magnetron sputtering alone. When applied to high-speed cutting tools, this results in a 40% increase in cutting efficiency and a 2.3-fold extension of tool life [19, 20]. The nc-TiC/a-C:H nanocomposite coating prepared using a hybrid technique combining medium-frequency magnetron sputtering and high-power pulsed magnetron sputtering achieves a hardness of up to 42.5GPa. After immersion in a 5% sulfuric acid solution for 72 hours, the corrosion rate was only 0.003mm/year, an 85% reduction compared to coatings produced by high-power pulsed magnetron sputtering alone, making them suitable for tool coatings used in corrosive environments[21]. Furthermore, AlCrN coatings prepared using this hybrid technology exhibited an oxidation weight gain of only 0.8mg/cm$^2$ during high-temperature oxidation testing at 1000℃, which is significantly lower than the 3.2mg/cm$^2$ observed for coatings prepared using a single technique, indicating a marked improvement in high-temperature stability[22].

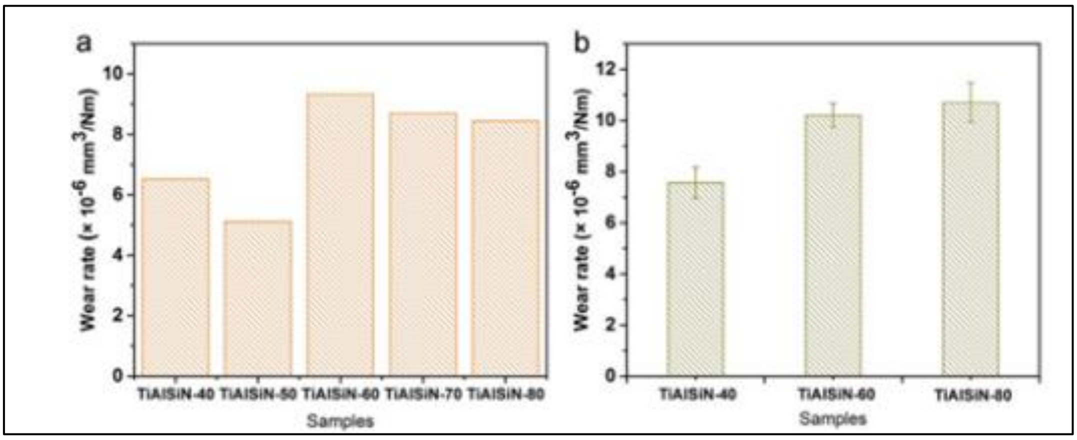

**Figure 4** Wear rates of the samples. (a) Ball-on-disc tests on the five samples, (b) reciprocating tests on TiAlSiN-40, 60 and 80 samples[22]

## 4.2. Applications in the Preparation of Wear-Resistant Lubricating Coatings

During the cutting process, friction between the cutting tool and the workpiece leads to accelerated tool wear, reducing cutting efficiency and machining quality; therefore, wear-resistant lubricating coatings have become a key area of development for tool coatings. High-power pulsed magnetron sputtering and its composite techniques can be used to prepare various wear-resistant lubricating coatings, such as MoS$_2$-Ti and VAlN/Ag. By controlling the composition and structure of the coatings, a balance between hardness and lubricity can be achieved, effectively reducing the coefficient of friction during the cutting process and minimizing tool wear.

MoS$_2$-Ti composite coatings prepared using a combination of DC magnetron sputtering and high-power pulsed magnetron sputtering exhibit significantly improved wear resistance when the Ti content is approximately 13.5%. The average coefficient of friction is as low as 0.04. Under a load of 5N and a sliding speed of 0.5m/s, the wear rate was

$1.8\times10^{-7}mm^3\cdot N^{-1}\cdot m^{-1}$, a 92% reduction compared to a single $MoS_2$ coating[23]. This coating can be applied to high-speed cutting tools and precision machining tools, effectively reducing friction losses during the cutting process and improving machining accuracy from IT8 to IT6. As shown in Figure 5, the VAlN/Ag multilayer coating was prepared using high-power pulsed magnetron sputtering composite technology. The Ag layer exhibits a nanotwin structure. After high-temperature friction testing at 300°C, the internal phase structure of the coating remained unchanged, with a friction coefficient and wear rate as low as 0.08 and $4.3\times10^{-5}$ $mm^3\cdot N^{-1}\cdot m^{-1}$. Under high-temperature cutting conditions, the tool life was more than three times longer than that of uncoated tools, and the cutting force was reduced by 25% during the cutting process[24].

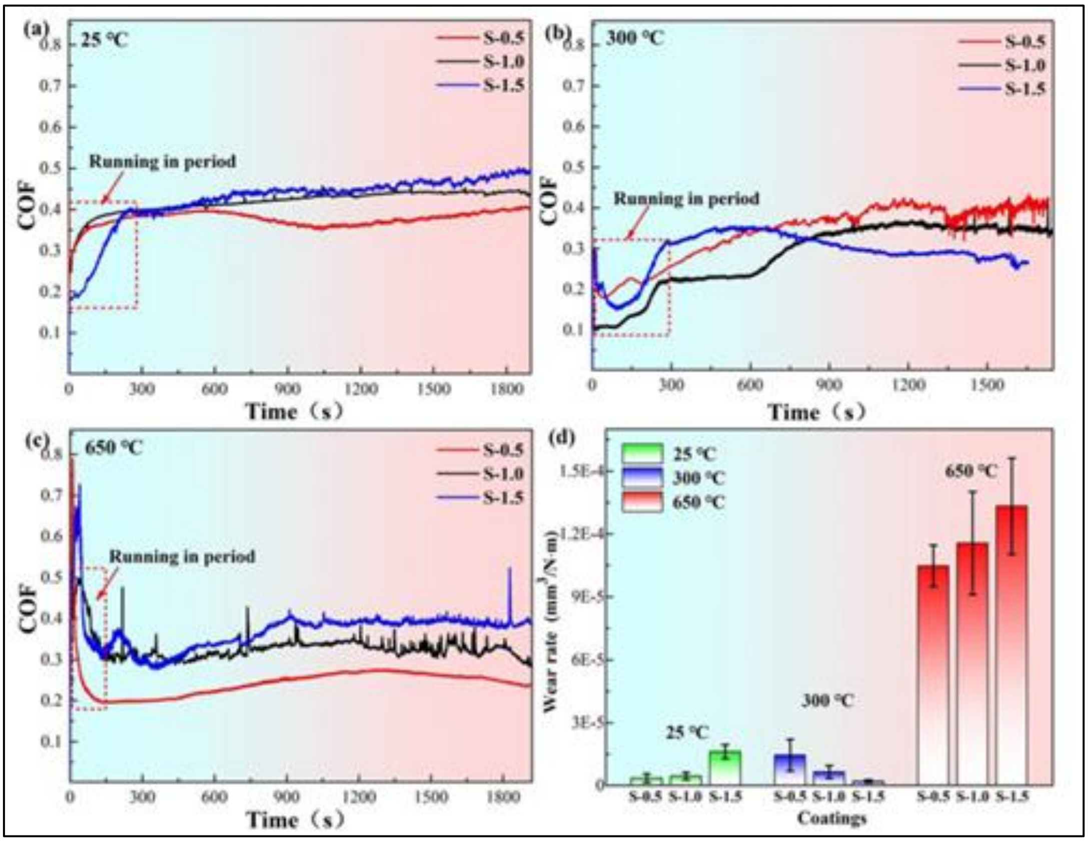

**Figure 5** The COF at 25 °C (a), 300 °C (b), 650 °C (c) and the WR (d) of coatings[24]

### 4.3. Applications in the Preparation of Coatings for High-End Precision Cutting Tools

High-end precision cutting tools impose extremely stringent requirements on coating surface quality, hardness, wear resistance, and dimensional accuracy. High-power pulsed magnetron sputtering and its hybrid technologies demonstrate unique advantages in the preparation of coatings for high-end precision cutting tools due to their excellent coating uniformity, low surface roughness, and controllable performance. For example, a Cr-Mo-Si-N nanocomposite coating prepared using arc ion plating combined with high-power pulsed magnetron sputtering exhibits a smooth and flat surface with a surface roughness (Ra) of only 0.08μm and no obvious defects, as well as a hardness of up to 26.5GPa. with a substrate-film adhesion of 85N. When applied to precision milling cutters, the tool runout during aluminum alloy machining decreased from 0.02mm to 0.008mm, the machined surface roughness Ra decreased from 0.4μm to 0.12μm, and the tool life was extended by 2.8 times[25].

In the preparation of coatings for specialized cutting tools in the semiconductor industry and precision cutting tools in the aerospace sector, high-power pulsed magnetron sputtering hybrid technology can produce high-purity, high-performance coatings that meet the operational requirements of cutting tools under extreme conditions. For example, ZrSiN coatings prepared using RF magnetron sputtering–high-power pulsed magnetron sputtering hybrid technology can increase the corrosion resistance of the tool substrate by 8 to 15 times; after 100 hours of immersion in a 3.5% sodium chloride solution, there were no obvious signs of corrosion, representing a 12-fold improvement in corrosion resistance compared to uncoated tools. When applied to precision milling cutters in the aerospace sector, cutting speeds of up to 180m/min can be achieved while machining the high-temperature alloy Inconel 718. This represents a 50%

increase compared to uncoated tools, with tool wear reduced by 75%, and the number of workpieces that can be machined with a single tool rising from 32 to 105.

## 5. Conclusion and Outlook

As an advanced physical vapor deposition (PVD) technique, high-power pulsed magnetron sputtering offers significant application value in the field of tool coating due to its high ionization rate, dense and uniform coatings, and strong substrate-film adhesion. Through integration with technologies such as DC magnetron sputtering, RF magnetron sputtering, MF magnetron sputtering, and arc ion plating, the issues of low deposition rates and high process costs associated with standalone high-power pulsed magnetron sputtering have been effectively addressed. This has achieved a synergistic improvement in coating performance and deposition efficiency, thereby advancing the development of tool coating technology.

Currently, significant progress has been made in the application of high-power pulsed magnetron sputtering and its hybrid technologies in the field of cutting tool coatings; however, some shortcomings remain: the control of process parameters for hybrid technologies is complex, and the synergistic mechanisms of different hybrid methods require further in-depth study; some hybrid technologies involve high equipment costs and significant energy consumption, which hinders large-scale industrial adoption; under extreme operating conditions, there is still room for improvement in the high-temperature stability and wear resistance of the coatings.

In the future, research on high-power pulsed magnetron sputtering and its composite technologies should focus on the following directions: First, conduct in-depth studies on the synergistic mechanisms of different composite technologies, optimize process parameters, achieve precise control over coating performance and deposition efficiency, and reduce process complexity and production costs; second, develop novel composite technologies by integrating new target materials and processes to further enhance the high-temperature stability, wear resistance, and corrosion resistance of coatings, thereby adapting them to more severe cutting conditions; Third, efforts should be made to promote the miniaturization and intelligentization of equipment for composite technologies, thereby reducing equipment costs and energy consumption to enable large-scale industrial applications; fourth, the application of these technologies should be expanded to the preparation of coatings for high-end precision cutting tools and specialty cutting tools. By addressing the needs of sectors such as new energy and aerospace, multifunctional, high-performance cutting tool coatings should be developed to advance cutting tool coating technology to a higher level.

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