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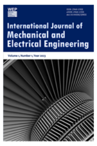

Research Status of Preparation Technology of Tungsten-based Coatings

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ABSTRACT

Due to its excellent properties such as high melting point, high hardness, strong corrosion resistance and low saturated vapor pressure, refractory metal W has been widely used in aerospace, nuclear industry, electronics and other fields. However, due to the scarcity and high cost of W resources, its large-scale application in large or complex structural components is severely restricted. In this context, the popularization and use of surface coating technology can not only prepare high-performance W-based coatings on the surface of low-cost substrates, but also solve the cost problem of W resource shortage. At present, the preparation technology of W-based coatings has formed a diversified pattern. Physical vapor deposition, chemical vapor deposition, spraying technology, laser cladding technology and electroplating and other methods each have unique advantages and applicable scenarios. This article will systematically sort out the preparation technology, performance optimization strategies and application status of tungsten-based coatings, analyze the existing problems in current research, and look forward to its future development direction.

KEYWORDS

Tungsten-based Coatings; Fabrication Processes; Properties; Applications.

1. INTRODUCTION

In modern industry and high-tech fields, the performance of materials under extreme environments often becomes the key bottleneck for technological breakthroughs. Due to its excellent comprehensive properties, refractory metal tungsten occupies an irreplaceable position in harsh scenarios such as high temperature and strong corrosion. Its melting point is as high as 3422 ℃, making it the element with the highest melting point among all metals. At the same time, tungsten has characteristics such as high hardness, strong corrosion resistance and low saturated vapor pressure, which enables tungsten to show unique advantages in applications such as hot-end components of engines in the aerospace field and structural materials of space nuclear reactors, providing an important guarantee for the stable operation of equipment under extreme environments[6-8].

However, tungsten is not perfect in practical applications, and its inherent limitations severely restrict its wider promotion. On the one hand, tungsten resources are scarce globally, and the mining and refining processes are complex, resulting in its high cost. This characteristic makes it difficult to apply pure tungsten materials to the production of large structural parts, greatly limiting its application potential in fields that require large-scale use of materials. On the other hand, tungsten has a high density, which is not suitable for large-scale production and manufacturing of workpieces or components with high quality requirements.

To break through the application limitations of tungsten materials and give full play to their excellent properties, coating technology has become an effective solution. Tungsten-based coating technology combines tungsten in the form of a coating on the surface of other substrate materials. While retaining the high performance of tungsten, it significantly reduces the consumption of tungsten, thus effectively reducing production costs and alleviating the pressure brought by the scarcity of tungsten resources. More importantly, by reasonably designing the composition and structure of the coating, the excellent properties of tungsten elements can be fully utilized. The research and development of tungsten-based coatings have important practical significance for expanding the application fields of tungsten materials and improving the relevant industrial technology level. Currently, the preparation methods of tungsten-based coatings include physical vapor deposition technology, chemical vapor deposition, electroplating, etc. In view of this, this paper aims to systematically review the research status of the preparation process of tungsten-based coatings.

2. PHYSICAL VAPOR DEPOSITION TECHNOLOGY

Physical vapor deposition technology (PVD) is a technology that, under vacuum conditions, uses physical methods to evaporate or decompose the target material in a solid or liquid state into molecules and atoms at the molecular and atomic scale and deposit them on the substrate, including thermal evaporation deposition, plasma evaporation plating, magnetron sputtering, ion plating, ion beam synthesis, and molecular beam epitaxy technology. Among them, magnetron sputtering technology and ion plating technology are commonly used methods for preparing tungsten-based coatings [9-11].

2.1. Magnetron Sputtering Technology

Magnetron sputtering technology fixes the material to be deposited on the substrate as the target to the cathode of the equipment cavity, and the substrate serves as the anode. During film coating, the cavity is pumped to a vacuum, argon gas is introduced into the cavity, and a high voltage is applied between the cathode and the anode to form a glow discharge. During the sputtering process, the coupling effect of the magnetic field and the electric field makes the electrons move in a spiral shape near the surface of the target, increasing the ionization rate of Ar molecules. The cations generated by ionization bombard the target at high speed under the action of the electric field, causing the target atoms to break away from the surface of the target and deposit on the substrate to form a coating. Magnetron sputtering technology has the advantages of good film/substrate adhesion, uniform and dense coating surface, high sputtering rate, and no pollution[12,13].

First, in terms of pure W coatings, research shows that magnetron sputtering technology can produce columnar crystal coatings with a dense structure[14]. Xu Fengyun prepared tungsten-based coatings using magnetron sputtering technology[15]. The research pointed out that pure W coatings deposited on CLAM steel at different sputtering powers are all columnar crystals and stable BCC-W phases, and no metastable phases were found. Among them, the W coating with a needle-like structure has relatively excellent anti-He plasma irradiation performance.

Second, in terms of tungsten-based coatings, research shows that the addition of W elements can improve the hardness of the coatings. Guo Zhongzheng et al, prepared CuW alloy coatings using magnetron sputtering technology[16]. The research found that when the atomic percentage of W is between 31.8 % and 54.8 %, the coating is amorphous. The addition of W elements increases the resistivity and hardness of the Cu coating.

In addition, the addition of W elements significantly improves the tribological properties of tungsten-based coatings. M. Lagarde et al. prepared NiW coatings using magnetron sputtering technology[17]. Minor changes in the Ni and W elements do not affect the particle size, roughness, and crystal texture of the NiW coatings. The addition of W elements can reduce the corrosion and passivation of the open-circuit. Li Zhonghao prepared WC coatings on stainless steel substrates using magnetron sputtering technology and found that the WC coatings have good anti-wear and friction-reducing properties in dry friction, deionized water, and seawater environments[18].

3. CHEMICAL VAPOR DEPOSITION TECHNOLOGY

Chemical vapor deposition is a process in which precursor gases undergo chemical reactions under specific reaction conditions by means of heating, plasma or photo-radiation excitation, etc., and metal or compound coatings are formed on the surface of the substrate[19]. Coatings prepared by chemical vapor deposition have excellent properties such as uniform and dense surfaces, low coating porosity, and suitability for preparing surface coatings for complex parts. However, there are also disadvantages such as the easy generation of toxic products, constraints on the selection of substrates and coatings for high-temperature deposition, and low deposition rates[20].

Chemical vapor deposition technology has different classification methods: according to the different excitation energy sources of reactants, it can be divided into thermal chemical vapor deposition, plasma chemical vapor deposition, laser chemical vapor deposition, metal organic compound deposition, etc.; according to the reaction type, it can be divided into solid-phase diffusion type, thermal decomposition type, hydrogen reduction type, displacement reaction type and reaction evaporation type; according to the different reaction temperatures, it can be divided into low-temperature deposition, medium-temperature deposition, high-temperature deposition and ultra-high-temperature deposition; according to the types of metal source precursors, it can be divided into metal halide chemical vapor deposition and metal organic chemical vapor deposition, etc.; according to the pressure of the reaction system, it can be divided into low-pressure, atmospheric-pressure and ultra-high-vacuum chemical vapor deposition, etc[21].

In the field of pure tungsten coatings, CVD technology exhibits unique advantages. Research shows that W coatings prepared by chemical vapor deposition usually exhibit a typical columnar crystal structure, and this microstructure endows the coatings with excellent mechanical properties and high-temperature stability. Zhang Zhaolin et al[22]. successfully prepared a dense and uniform columnar crystal pure tungsten coating on the surface of gun steel substrate through CVD technology, and this coating exhibits excellent ablation resistance, providing an effective solution for the surface protection of key components of high-energy weapons. Du Jihong et al[23]. prepared W coatings on molybdenum substrates, and it was found that the deposition conditions have a significant impact on the preferred orientation of the crystal structure of the coatings. The optimized coatings show good interfacial bonding force and thermal shock resistance, and are suitable for the protection of components under high heat load conditions[21].

In the research of tungsten carbide coatings, some scholars used atmospheric pressure chemical vapor deposition technology, with dimethyl ether (CH_3OCH_3) as the carbon source, tungsten hexafluoride (WF_6) as the tungsten source, and hydrogen (H_2) as the reducing agent, and successfully prepared tungsten carbide coatings on disk-shaped and hexagonal copper substrates. Systematic research shows that the dimethyl ether partial pressure is the key parameter affecting the coating properties: as the partial pressure changes, the coating phase transforms between WC and W, W_2C and W, and the microstructure and growth rate also change accordingly. In-depth analysis reveals that there are essential differences in the mechanism of coating phase content change at low and high dimethyl ether partial pressures, and based on this, a quantitative relationship model between the coating deposition rate and the dimethyl ether partial pressure is established. The deposition experiment on the hexagonal substrate further verifies the influence law of the dimethyl ether partial pressure on the coating growth kinetics, providing theoretical guidance for the controllable preparation of tungsten carbide coatings on the surfaces of complex-shaped workpieces[24].

To overcome the limitations of a single CVD process, researchers explored composite process routes. Zhang Danhua et al. used chemical vapor deposition and hot isostatic pressing processes to prepare tungsten coatings with a uniform and flat columnar crystal structure on oxygen-free copper surfaces. The test results show that the interfacial bonding strength is greater than that of the brazing bonding method connected by brazing, and no obvious damage is found after 5 thermal cycles in a hydrogen atmosphere at 970 °C, indicating good thermal shock resistance. This CVD-HIP composite process provides a new idea for solving the interfacial failure problem caused by the difference in thermal expansion coefficients in the copper-tungsten system, and has important reference value for the development of plasma-facing materials in fusion reactors.

4. ELECTROPLATING TECHNOLOGY

Electroplating is a process of depositing a metal or alloy coating on the surface of a metal or conductive material (non-conductors need to be pre-treated for conductivity) using the electrolysis principle. Its core functions include protecting the substrate (anti-corrosion, wear resistance) and beautifying the appearance, and at the same time, it can expand special properties such as conductivity and high temperature resistance. From the perspective of technical classification: it can be divided into direct current electroplating, pulse electro-deposition, etc. according to the current form; it can be divided into conventional electroplating, brush plating, and vacuum electroplating according to the deposition scenario. Among them, pulse electro-deposition is the mainstream electroplating method for preparing high-performance tungsten-based coatings because it can regulate the microstructure of tungsten-based coatings; brush plating is often used for local repair of tungsten-based coatings or on-site plating of large substrates. Both are important technologies in the field of electroplating preparation of tungsten-based coatings. Among them, pulse electro-deposition technology and brush plating technology are often used in the preparation of tungsten-based coatings[25-27].

4.1. Pulse Electro-deposition Technology

Electrochemical deposition is a material preparation method based on the principle of electrochemical reaction. Its essence is to construct a cathode - anode circuit in a specific electrolyte system by applying an external electric field (either a direct - current or a pulse power supply), which enables metal cations in the electrolyte solution to gain electrons on the cathode surface and be reduced to metal atoms, thus forming a dense metal coating on the substrate surface[28]. Among numerous electrodeposition techniques, the pulse electrochemical deposition process has attracted much attention due to its unique advantages: this technology can be carried out at room temperature or lower temperatures, significantly shortening the process cycle and improving the deposition efficiency; at the same time, it has the characteristics of simplified operation procedures, easy control of process parameters, and high production safety, providing an efficient and reliable technical approach for the controllable preparation of functional metal coatings[29].

In terms of composition and microstructure regulation, some studies have shown that the content of W elements has a decisive influence on the properties of NiW alloy coatings. The research by Gao Qiang et al[30]. confirmed that with the increase of W content, the NiW coating significantly improves the hardness of the 45 - steel substrate, and at the same time, the wear resistance is improved synchronously. Liu Shuang successfully prepared a nanoscale nickel - tungsten alloy coating by optimizing the main salt concentration, obtaining a higher W content, a finer grain structure, and better corrosion resistance[31]. The comparative experiments by D. Figuet et al. further confirmed that the introduction of W elements can significantly refine the grain size and greatly improve the wear resistance of the coating[32].

In terms of the correlation between microstructural evolution and properties, J. Druga et al[33]. prepared NiW alloys with different W contents (grain size <50 nm) through pulse electroplating and pulse reverse electroplating techniques, revealing the complex relationships among W content, phase structure, and properties: when the W content is 5 at.% and the crystalline phase is dominant, the corrosion resistance of the coating is better than that of pure nickel; while when the W content further increases and the amorphous phase dominates, the corrosion resistance significantly decreases. The study also found that the structure dominated by the amorphous phase would lead to an increase in wear rate and friction coefficient, which might stem from the special response mechanism of the amorphous region to mechanical stress. In addition, Narasak Sunwang et al[34]. used reverse pulse electroplating technology to control the W content and nanocrystalline grain size of the coating to prepare NiW coatings. This study explored the relationships among process parameters, microstructures, and mechanical responses of electroplated NiW coatings at high temperatures of 700 – 1100 °C. The results showed that: 700 °C heat treatment improved the hardness of alloys with high W content (22 at.%) and small grains (3 nm) but slightly decreased their wear resistance; extending the annealing time or increasing the temperature, although a second phase would form, would still exacerbate grain growth, resulting in a decrease in both hardness and wear resistance; for alloys with low W content (6 at.%, 13 at.%) and large grains (13 nm,56 nm), grain growth was more obvious and the hardness continued to decrease. In summary, electroplated NiW coatings with high W content can be used as candidate materials for high temperatures[34].

In the research on the corrosion resistance mechanism, Pedro de Lima-Neto et al[35]. systematically compared the electrochemical behaviors of electrodeposited Cr coatings and NiW coatings in NaCl solution. The study found that reducing the current density could reduce the defects of the NiW coatings and promote the transformation of the surface morphology from fine spherical particles to coarser polycrystalline structures. In the chloride environment, both coatings corroded, but the corrosion morphologies and products were quite different: Cr_2O_3 and $Cr(OH)_2$ were formed on the surface of the Cr coatings, while $Ni(OH)_2$, NiO and WO_3 were formed on the NiW coatings. Notably, although cracks appeared in the NiW coatings during the heat treatment process, the hardness increased significantly with the increase in temperature, showing excellent thermal stability and promising to replace the traditional hard Cr coatings[36]. Liu Shuang developed nanoscale nickel-tungsten alloy coatings using pulse electrodeposition technology. The study found that compared with direct current plating, pulse plating could obtain coatings with higher tungsten content, higher hardness, finer grains, and better corrosion resistance.

4.2. Brush Plating Technology

Brush plating technology is an advanced surface treatment method that forms a metal or alloy protective layer on the surface of workpieces through local electrochemical deposition. This technology was initially mainly applied to the field of on-site repair and remanufacturing of mechanical components. With the deepening of materials science research and technological innovation, brush plating exhibits significant advantages different from traditional surface coating processes: its operation mode is flexible and variable, and it can be processed according to the geometric shape and usage requirements of workpieces; the material systems that can be deposited are rich and diverse, covering a variety of functional metal and alloy coatings; the scope of application is wide, and it can be applied from precision instruments to large-scale equipment. These unique characteristics make brush plating technology increasingly prominent in the field of modern surface engineering and become an important and indispensable part of the material surface modification technology system[37].

In terms of antioxidant and tribological properties, Jie Hua et al[38]. found that the NiW coating prepared by the electro-brush plating technique exhibited excellent antioxidant ability at 600 °C, but as the temperature continued to rise, the internal stress in the coating increased, leading to a decline in antioxidant performance. L. Zhu et al[39]. found that as the W content increased, the structure of the NiW coating underwent a transformation from polycrystalline fcc-Ni type to amorphous state and then to orthorhombic structure. At the same time, the grain size was refined and the density increased. This change in microstructure caused more plastic deformation in the alloy and more surface scratches, which had a significant impact on tribological properties.

In the research on the wear repair of diesel engine crankshafts, Ding Lihong et al[40]. used the electro-brush plating process to prepare a Ni-W alloy coating on the surface of the failed crankshaft, providing key theoretical support for the process optimization and performance regulation of electro-brush plated tungsten-based coatings. Through orthogonal experiments, they clarified the primary and secondary effects of working voltage, electro-brush plating time, and cycle rate on the wear resistance of the coating. It was found that when the process parameters were working voltage 14 V, deposition time 20 min, and cycle rate 6-8 m/min, the wear resistance of the coating was far superior to that of the nodular cast iron matrix. Moreover, at this voltage, when the coating thickness reached the standard, the hardness reached its peak, and at the same time, the bonding force between the coating and the matrix and the overall tensile strength were significantly improved, proving that the tungsten-based coating prepared by this process could meet the requirements of crankshaft remanufacturing.

Chen Yuandi prepared self-lubricating In and Ni-W(D) composite coatings on the surface of Cr12MoV die steel by electro-brush plating, successfully achieving the synchronous improvement of the size repair of worn dies and surface wear resistance[41]. The research by Yuhan Hu et al[42]. showed that W could not be directly deposited from an aqueous solution, but it could be induced to co-deposit under the action of Ni ions, forming a $Ni_{17}W_3$ solid solution with Ni as the solvent and W as the solute. The occupation of Ni lattice positions by W atoms caused lattice distortion, significantly increasing the hardness. The coating with a high W content showed a dense spherical structure and excellent corrosion resistance.

In addition, S.B. Hua et al[43]. innovatively used the electro-brush plating technique to prepare a NiW interlayer to enhance the bonding strength of the TiN coating. The study found that the single TiN coating had poor wear resistance at high temperatures, while the TiN composite coating with NiW as the transition layer showed excellent performance in high-temperature environments. This is mainly attributed to the crystallization and precipitation hardening that occurred in the transition layer at high temperatures, as well as the diffusion layer and duplex composite structure formed at the interface. These changes effectively improved the overall hardness and interfacial bonding strength of the composite coating, endowing it with excellent thermal stability.

5. LASER CLADDING TECHNOLOGY

Laser cladding is an advanced surface modification process. Its working principle is to irradiate the surface of the workpiece with high-density laser energy (the power density ranges between 10^4 and 10^6 W/cm^2), and at the same time introduce the cladding material into the irradiation area by means of pre-placement or synchronous powder feeding. Under the action of laser heat, the surface layer of the substrate and the cladding material are melted together to form a dynamic molten pool, which then undergoes a rapid cooling and solidification process, and finally forms a metallurgical bonding layer with a unique microstructure. The cladding layer prepared by this technology shows significant advantages, including low substrate dilution, fine solidification structure, and strong interfacial bonding. At present, laser cladding technology has been widely used to improve the surface functional characteristics of components, especially in enhancing the material's resistance to wear failure, chemical corrosion, and high-temperature oxidation. Compared with traditional surface treatment technologies, the laser cladding process has multiple advantages: precise and controllable processing, limited heat-affected area, outstanding production efficiency, low energy consumption, and at the same time can achieve efficient utilization of materials, meeting the development needs of modern manufacturing for green and low-carbon technologies[44-47].

The tungsten-based coatings prepared by laser cladding technology have certain wear resistance. Shan Shuai-shuai et al[48]. prepared WC-reinforced FeCoNiCrAl high-entropy alloy composite coatings on the surface of 316 L stainless steel by laser cladding technology, and studied the effects of different WC addition amounts (10 %, 15 %, 20 %, 25 % and 30 %) on the microstructure and properties of the composite coatings. With the increase of WC content, the bottom and top of the cladding layer changed from columnar crystals and cellular crystals to dendrites and irregular cellular crystal structures between dendrites, the hardness of the coating increased, and the wear resistance of the coating was also improved. Chen Yan-bin et al. cladded Cu/WC composite coatings on the surface of 45 steel matrix by laser cladding technology, and found that the increase of WC addition amount made WC particles increase, showing a duplex structure of α-Cu solid solution + WC. When WC≤30 %, there was no obvious melting, and when it exceeded 30 %, fine dot-like WC appeared. The transition zone at the bottom of the cladding layer was steel matrix + WC, and WC was more likely to melt in the steel matrix and cooled to precipitate tungsten-containing compounds. In terms of wear resistance, when grinding against a 40 Cr grinding wheel, the friction coefficient and wear amount were the smallest when WC was 10 %; when grinding against a cemented carbide grinding wheel, the friction coefficient was small when WC was 30 %, and the wear amount was small when WC was 10 %. Fu Shuo et al[49]. used laser cladding technology to coat WC gradient coatings on the surface of titanium alloy drill pipes to improve the wear resistance of the drill pipes. The gradient coatings increased the wear resistance of the uncoated drill pipes by 1.45 times. A 10 μm mutual diffusion zone was formed between the gradient coatings and the matrix, improving the bonding force of the coatings.

In addition, Wu Xin-wei et al[50]. prepared Ni-based WC metal ceramic cladding layers on A3 steel plates by laser cladding technology, and found that cracks existed in the Ni-based WC metal ceramic cladding layers prepared by laser cladding. The increase of WC content could reduce the crack propagation rate of the cladding layer.

In summary, laser cladding technology has significant advantages in the preparation of WC-reinforced composite coatings. By reasonably controlling the WC content, the type of matrix material and the coating structure design, surface protective coatings with excellent properties can be developed for different working conditions. These research results provide important theoretical basis and technical support for the application of WC-reinforced composite coatings in the engineering field.

6. THERMAL SPRAYING TECHNOLOGY

Thermal spraying technology is an important material surface modification technology. Due to its characteristics such as high efficiency, small deformation, and controllable coating thickness, it is widely used in the fields of aviation, aerospace, chemical industry, shipbuilding, etc. It is particularly crucial in the aviation field and is the core technology for the manufacture of aircraft and engine components, which is of great significance for improving the performance of equipment. It mainly includes flame spraying, arc spraying, plasma spraying, high-velocity oxy-fuel spraying, detonation spraying, etc. Since the “Sixth Five-Year Plan”, China has actively promoted this technology and achieved remarkable results. Among them, plasma spraying technology can achieve the coating of large-area and complex-structured surfaces and can also achieve in-situ repair, effectively solving the problems of high specific gravity and poor machinability of workpieces[51,52].

Researchers Jian Zhonghua et al[53]. from Beijing Institute of Technology used high-velocity thermal spraying and plasma spraying technologies to prepare a W coating on the copper surface and studied the effects of the two spraying technologies on the properties of the W coating. The study found that the surface of the W coating prepared by the high-velocity oxy-fuel technology was unevenly melted and a continuous W coating could not be formed. The W coating prepared by plasma spraying technology had a dense surface, low porosity, and high bonding strength.

In order to improve the problem that the W coating directly sprayed on the copper substrate is prone to peeling, researchers such as Ma Wenyou used low-pressure plasma spraying technology to prepare a multi-layer structure on the copper substrate in sequence: first, spray a Ni-Cu transition layer and achieve metallurgical bonding with the substrate through laser remelting; then prepare a Ni-W intermediate layer on the transition layer; finally, spray the W layer and perform laser remelting again to improve the cohesive strength of the W layer and reduce the porosity. This study effectively alleviated the problems caused by the difference in thermal expansion coefficients between Cu and W through gradient structure design, and at the same time significantly enhanced the bonding performance between the coating and the substrate and the cohesive strength of the coating itself by means of laser remelting technology[54].

In addition, as a key plasma-facing material for fusion reactors, the performance of the W coating directly affects the operation safety and lifespan of the device. Researchers such as Song Shuxiang successfully prepared high-quality W coatings on an oxygen-free copper substrate using plasma spraying technology, verifying the feasibility of this technology in the preparation of fusion materials. Further research shows that the spraying environment has a decisive impact on the performance of the W coating. Comparative experiments by Zhong Fali et al. revealed that the W coating prepared in a vacuum environment has lower porosity, higher thermal conductivity, and less oxygen and other impurity contents compared to the coating prepared in an atmospheric environment. These structural advantages enable the W coating prepared in a vacuum environment to exhibit significantly better thermal load-bearing capacity and thermal fatigue resistance, providing important technical support for the surface protection of key components in fusion devices.

In summary, thermal spraying technology, especially plasma spraying technology, shows great application potential in the field of W coating preparation. By means of process optimization, structural design, and environmental control, etc., the key technical problems in the preparation process of high-melting-point metal coatings can be effectively solved, providing reliable solutions for the surface protection of materials in high-end equipment fields such as aerospace and nuclear energy.

7. SUMMARY

This paper systematically reviews the research status of the mainstream preparation processes of tungsten-based coatings. The results show that physical vapor deposition, chemical vapor deposition, electroplating, laser cladding, and thermal spraying technologies each have their own advantages and applicable scenarios. The tungsten-based coating prepared by magnetron sputtering technology has good adhesion and a dense surface, and performs outstandingly in the field of anti-plasma irradiation; chemical vapor deposition can achieve the preparation of coatings for complex parts, and the coating has low porosity, but the high-temperature deposition conditions have constraints on the substrate; pulse electro-deposition can optimize the microstructure of the coating by adjusting process parameters, improving hardness and wear resistance, and brush plating is suitable for local repair; laser cladding can prepare high-hardness composite coatings to improve the wear resistance of the substrate; plasma spraying can prepare tungsten coatings with low porosity and high thermal conductivity in a vacuum environment, meeting the requirements of special scenarios such as fusion reactors.

However, there are still deficiencies in current research, such as the bonding stability problem caused by the difference in thermal expansion coefficients between the coating and the substrate, the relatively high preparation cost of some processes, and the need to improve the long-term performance of the coating under complex working conditions. In the future, it is necessary to further optimize the coating composition and structure design, develop low-temperature, high-efficiency, and green preparation processes, and strengthen the research on the performance regulation of the coating under extreme environments to promote the wider application of tungsten-based coatings in high-end fields such as aerospace and nuclear industry.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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