Science Press

REVIEW

Research Status and Prospects of Platinum Group Metal Coatings with High-Temperature Oxidation Resistance

Ding Chenxi[1], Liu Zhongyu[1,2], Fang Zhen[1], Wang Haoxu[1], Lv Biao[1,3], Hu Zhenfeng[1]

[1] National Innovation Institute of Defense Technology, Academy of Military Sciences, Beijing 100071, China; [2] School of Materials Science and Engineering, Shenyang Ligong University, Shenyang 110159, China; [3] Unit 63723 of the Chinese People's Liberation Army, Xinzhou 036300, China

Abstract: Platinum group metals have high melting points, strong corrosion resistance, stable chemical properties, and low oxygen permeability in high-temperature oxygen-containing environments. As thermal protective coating materials, they have gained essential applications in the aerospace field and have excellent prospects for application in frontier military fields, such as protecting hot-end components of hypersonic aircraft. This research reviewed the latest research progress of platinum group metal coatings with high-temperature oxidation resistance, including coating preparation techniques, oxidation failure, and alloying modification. The leading preparation techniques of current platinum group metal coatings were discussed, as well as the advantages and disadvantages of various existing preparation techniques. Besides, the intrinsic properties, failure forms, and failure mechanisms of coatings of single platinum group metal in high-temperature oxygen-containing environments were analyzed. On this basis, the necessity, main methods, and main achievements of alloying modification of platinum group metals were summarized. Finally, the future development of platinum group coatings with high-temperature oxidation resistance was discussed and prospected.

Key words: platinum group metal coatings; preparation technique; high temperature; oxidation resistance; alloying modification

1 Introduction

When the speed of a vehicle exceeds Mach 5, it is called a hypersonic aircraft. Because of its extremely high speed and long flight distance, hypersonic aircraft plays a profound role and exerts significance in the military, political, and economic fields. The hypersonic aircraft is a strategic weapon that every country competes for[1-2]. However, it is subject to strong oxidation ablation as well as violent airflow washout in the course of flight. Hence, the service requirements for their hot-end components are high. Hypersonic aircraft's hot-end component materials mainly include ultrahigh-temperature ceramics, carbon fibres, and carbon fibre-reinforced composites, as well as refractory metals and their alloys[3]. Ultrahigh-temperature ceramics have a variety of definitions, and they are usually defined as nitrides. From a chemical analysis perspective, ultrahigh-temperature ceramics are nitrides, borides, and carbides of some transition metal with high melting points (Hf, Zr, Ta, Ti, Nb, et al)[4-6]. Although they have excellent strength and oxidation resistance in high-temperature environments, ultrahigh-temperature ceramics are brittle and difficult to mould. Carbon fibre composites and refractory metals also have excellent thermal shock resistance and a certain degree of corrosion resistance. However, they are prone to oxidation in high-temperature oxygen-containing environments above 1800 °C. The oxides will be flaked off or volatilized, reducing the high-temperature thermal protection characteristics of the components or even causing failure[7-8]. These problems can be effectively solved by covering the surface of hot-end parts with a high-temperature oxidation-resistant coating, and the performance of the high-temperature materials can be fully used.

Platinum group metals (Ru, Rh, Pd, Os, Ir, and Pt) with extremely low oxygen permeability, chemical stability, high

strength, and high melting points are ideal protective coatings on hot-end components, providing good protection and prolonging the service life of hot-end components. Platinum group metals are all located in the fifth and sixth cycles of group VIII in the periodic table. Except for Ru and Os, which have hexagonal close-packed structures, the remaining elements have face-centred cubic structures with stable physical properties, extremely high melting and boiling points, and strong atomic bonding. Compared with other high-temperature antioxidant coating materials, platinum group metal coatings have the following advantages: (1) high metal strength and good ductility of monomaterial metal; (2) ultrahigh melting point and very low vapor pressure; (3) specific chemical properties for easy deposition and the nature of stability; (4) excellent oxidation resistance.

In this review, common preparation techniques of high-temperature antioxidant platinum group metal coatings were introduced, and their advantages and disadvantages were compared. The antioxidant properties and failure mechanisms of platinum group metal coatings in high-temperature environments were discussed, and the improvement and enhancement of the high-temperature antioxidant performance of platinum group metal-modified coatings were also mentioned. The future development direction of platinum group metal coatings in the key areas was prospected.

2　Preparation Techniques of Platinum Group Metal Coatings with High-Temperature Oxidation Resistance

Platinum group metal coatings are prepared by a wide variety of methods, including metalorganic chemical vapor deposition (MOCVD), atomic layer deposition (ALD), double glow plasma (DGP), magnetron sputtering (MS), and electrodeposition (ED).

2.1　MOCVD technique

MOCVD technique is one of the commonly used techniques to prepare platinum group metal coatings, which is based on the principle that metalorganic compounds are used as deposition precursors to generate a deposit coating on the matrix surface through thermal decomposition reactions[9]. MOCVD technique is one of the chemical vapor deposition (CVD) techniques. Compared with common CVD techniques, MOCVD can better control the deposition rate and coating thickness, and the coatings can be deposited at low temperatures. Fig. 1 shows the schematic diagram of the device for MOCVD preparation of platinum group metal coating. The whole device consists of a deposition chamber, a heating device, and a gas circuit system, which uses inert gases to transport the gaseous precursor compounds to the deposition chamber. The precursor decomposes into a metal coating deposited on the matrix surface by heating. At the same time, a vacuum pump is used to exhaust the irrelevant gases generated by decomposition[10].

There are a few reports on preparation of Rh and Os coatings using MOCVD technique. Os is easily oxidized and
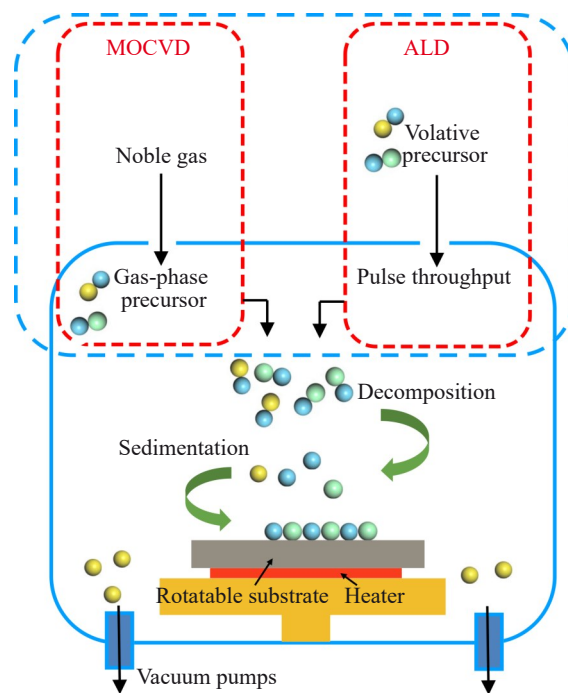

Fig.1　Schematic diagram of preparation device of platinum group metal coating by MOCVD and ALD techniques

volatilized due to its nature. The precursors used to prepare Rh coatings are complex and have too many impurities during the deposition process, resulting in inferior coating quality[11]. Pd and Ru coatings are commonly used as electrical contacts and diffusion barrier layers[12–13], but they are rarely used for high-temperature protective materials. The Ir and Pt coatings prepared by MOCVD technique have high densities and good oxidation resistance at high temperatures. Ir coatings prepared by MOCVD technique have been widely used in aerospace applications[14]. Harding et al[15] pioneered Ir(acac)₃ as a precursor, enabling the MOCVD technique to prepare high-purity Ir coatings at lower reaction temperatures. Due to the controllable thickness and high success rate of the prepared coatings, Ir(acac)₃ is widely used. Goto et al[16] used a hot-wall reactor, while Hu et al[11,17–18] used a cold-wall reactor. Both researches explored the variation patterns of deposition rates and deposition temperatures of Pt and Ir coatings prepared by MOCVD technique. Goto et al[16] found that the coatings deposited on quartz and sapphire satisfy the deposition kinetic law of the Arrhenius equation, while Hu et al[11,17–18] found that the deposition rates of Pt and Ir on molybdenum matrices were the fastest at 550 and 750 °C, respectively, and the deposition rates were gradually decreased with the increase in temperature. Therefore, the proper temperature and carrier gas flow rate can enhance the densification and high-temperature oxidation resistance of platinum group metal coatings. Goto[16,19] and Maury[20] et al found that the passage of a small amount of oxygen could reduce the embedding of carbon in acetone and enhance the coating quality. Gelfond et al[21] used pulsed MOCVD with in-situ mass spectrometric control of the deposition process to prepare Ir coatings with denser

nanocrystalline structures, which could control the oxygen penetration more efficiently at high temperatures.

MOCVD technique for preparing platinum group metal coatings has been matured and perfected, and the acetylacetonate platinum group metals are still the most efficient available precursor compounds. The research on MOCVD technique in recent years focuses on the development of novel precursors, such as (CH3)₃Pt(L)Py and subvalent iridium precursors[22–26]. Reducing the decomposition temperature of the complexes and enhancing the reaction window are the key issues to improve MOCVD technique. Currently, the high cost and low utilization rate of precursors in MOCVD process are the main problems for application in the industrial field.

2.2 ALD technique

ALD is a new preparation technique based on CVD technique. Its principle is that the gas-phase precursor is pulsed alternately into the reactor, chemically adsorbed on the deposition matrix, and reacted to form a deposited coating. The most crucial feature of ALD is that the surface reaction is self-limiting, which makes the coating prepared by ALD technique have the characteristics of uniform thickness and good densification, and the choice of matrix materials is more diversified. Thus, the thickness of the coating submonolayer can be uniformly and accurately controlled over a large area[27].

More and more reports are related to the preparation of platinum group metal coatings by ALD technique, but most of them are related to the research on catalysis and batteries[28–30]. Ir and Pt coatings have been studied in terms of high-temperature oxidation resistance. Pt(MeCp)Me₃ and lr(acac)₃ are usually selected as precursors for the preparation of Pt and Ir coatings by ALD technique. Schmitt et al[31] found that iridium coatings could be grown on any matrix after 100 deposition cycles. The coating size and shape were closely related to the matrix material, so the coating properties could be changed by adjusting the matrix material. Although this method proves the feasibility of preparing Ir coatings on high-temperature structural materials, the quality of the coatings needs to be further investigated and verified. Gao et al[32–33] not only prepared Ir coatings with (111)-optimized orientation on the surface of Mo matrix using Ir(acac)₃ as the precursor, but also proposed a novel idea of composite preparation of coatings. The Ir coating was deposited by the combined preparation method of ALD and MOCVD techniques, which can take advantage of the fast deposition rate of MOCVD and retain the continuous and dense characteristics of the Ir coating prepared by ALD technique. The high-temperature oxidation resistance was verified. Research on new precursors facilitates the enhancement of coating quality. Hong et al[34] used tricarbonyl-(1,2,3η)-1,2,3-tri(tert-butyl)-cyclopropenyl-Ir as a novel precursor for deposition under oxygen atmosphere, and the initial growth principle and growth law of the Ir coating were investigated. The results show that smooth, continuous, and dense Ir coatings can be formed on the matrix surface at high temperatures. However, the growth temperature and the matrix surface structure restrict the

density and size of the Ir coatings. Park et al[35] prepared Ir coatings using tricarbonyl cyclopropenyl as the precursor. The introduction of the cyclopropenyl ligand can improve reactivity during the deposition process.

Although the platinum group metal coatings prepared by ALD have good uniformity, controllable thickness, and dense structure, the coating density is closely related to the matrix composition, and the deposition rate is slow. Compared with other preparation methods, ALD technique has no apparent advantages.

2.3 DGP technique

DGP technique is a new physical vapor deposition (PVD) technique developed based on the plasma nitriding technique and proposed by Xu et al[36–37]. Its principle is to form a coating by generating a low-temperature plasma with a glow discharge and sputtering the desired elements onto the target matrix in a high-vacuum environment[38–39]. As shown in Fig.2, DGP technique uses a three-electrode structure, containing an anode, a cathode for placing the substrate, and a source electrode for placing the coated target material. The plasma generated during the glow discharge process bombards the source electrode, and the target elements move towards the substrate under the action of the electric field to form the coating. The coatings prepared using DGP technique have uniform composition, high purity, and dense structure. The technique is conducted at low temperatures and has a high deposition capacity.

The research on the preparation of high-temperature oxidation-resistant coatings by DGP technique mainly focuses on metals Ir and Pt. In Ref.[40–43], DGP technique was used to prepare Ir coatings on the surface of refractory metal and high-temperature resistant material[38,44]. The coating structure was columnar crystal with (220)-preferred orientation. Although the coating deposition rate (2.9–5.7 μm/h) is greatly affected by the base material and working pressure, it is also slightly higher than that of some other techniques. Zhang et
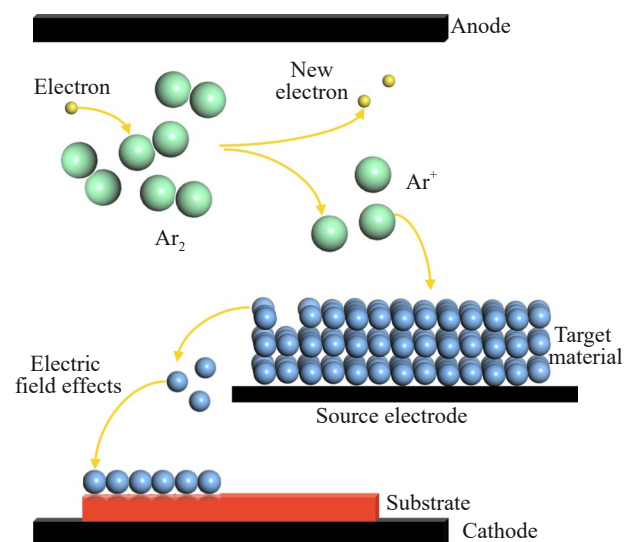

Fig.2 Schematic diagram of preparation mechanism of platinum group metal coating by DGP technique

al[45] prepared continuous and dense Ir coating on the surface of WC ceramics by DGP technique and conducted nanoindentation and scratch tests, proving that the coating had good mechanical properties with a coating hardness of 800 HV and an elastic modulus of 644 GPa. Wu et al[46–47] also conducted relevant studies by preparing Pt coating under different air pressure environments. They found that the preferred orientation of the coating was (220), and the coating and the matrix were well combined (binding force>60 N). However, the Pt coating prepared by DGP technique has some pores, and the porosity is increased with the increase in air pressure. Excessively high porosity makes the coating prone to fail at high temperatures.

Although the deposition rate of platinum group metal coatings prepared by DGP technique is fast and the target utilization rate is high, the compactness of the coatings prepared by DGP technique is lower than that by other preparation techniques. There are fewer research reports on the preparation of platinum group metal coatings by DGP in recent years.

2.4 MS technique

The operating principle of MS technique is to use the charged high-energy ions, which are accelerated by an electric field, to bombard the target, causing atoms and molecules in the target to escape and be deposited on the matrix surface, as shown in Fig. 3. This process has high molding quality and uniform and dense coating. MS technique is a more mature PVD preparation technique. Currently, platinum group metal coatings prepared by MS technique are mostly used in sensitive components as well as semiconductors[48–49], and their applications in the preparation of coatings with high-temperature oxidation resistance are rarely reported.

Mumtaz et al[50–51] deposited Ir coatings on the surface of C/C composites using radio frequency (RF)-MS and direct-current (DC)-MS, and it was found that the Ir coatings prepared by RF-MS were more homogeneous and intact by comparison. It was further found that at 800 °C, the Ir coatings heat-treated in N_2 atmosphere were dense, the surface was free of cracks and dislocations, and the pores were significantly
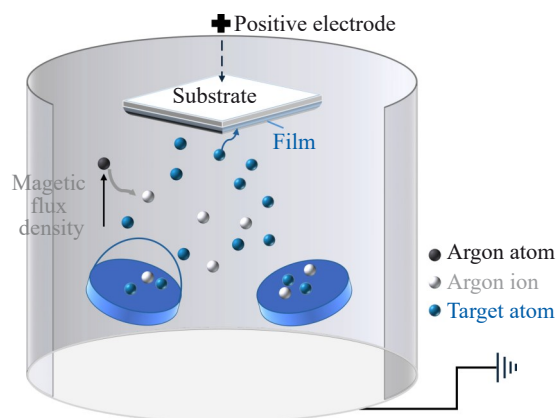
reduced or even eliminated, compared with those before the high-temperature treatment. El-Khakani et al[52] used the sputtering of Ir targets with argon to achieve the preparation of Ir coatings and to investigate the effect of different argon pressures and RF power densities on the coating pattern. It was found that the Ir coatings prepared by MS technique all have (111)-optimally oriented polycrystalline structures, and the argon pressure had a significant effect on the coating structure. Huo et al[53] prepared (100)-oriented Ir coatings on the MgO matrix and investigated the influence of MS time on the growth of Ir coatings. It was found that the (100) preferential orientation of Ir coatings changed to (200) preferential orientation with the prolongation of deposition time. The surface roughness was also increased and then decreased with the prolongation of deposition time. The sputtering time has a greater effect on the densification of Ir coatings.

Although the quality of the coatings prepared by MS technique is high, and the coatings are less affected by the matrix material, the low target utilization rate and expensive production cost significantly restrict the development of MS technique for the industrial preparation of platinum group high-temperature antioxidant coatings. At the same time, the coating deposited by MS technique is thin, and further improvement and optimization of MS technique are needed in the future.

2.5 ED technique

ED technique is a commonly used process for coating preparation and surface treatment. It contains a variety of preparation systems, such as aqueous solutions, nonaqueous solutions, and molten salts. The molten salt ED process is a simple process with fast deposition rate and low cost, compared with other preparation methods, as shown in Fig. 4. The coating prepared by ED process has good densification, good coating uniformity, and large deposition thickness. Thus, ED technique is an ideal process for preparing the high-temperature antioxidant coatings of platinum group metals[54].

Currently, more reports are related to ED-prepared Ir coatings using the ternary eutectic system of NaCl-KCl-CsCl. Compared with that in the NaCl-KCl, LiCl-KCl, and Li-Cl-NaCl-KCl systems[55–57], the Ir^{3+} in this system exists in the

Fig.3 Schematic diagram of preparation mechanism of platinum group metal coating by MS technique

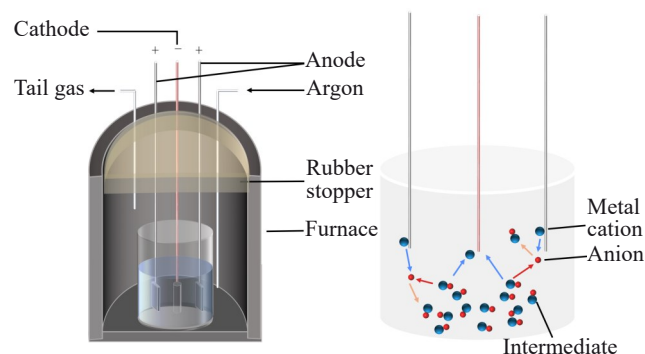
Fig.4 Schematic diagram of preparation mechanism of platinum group metal coating by ED technique

form of $[IrCl_6]^{3-}$. Besides, due to the presence of Cs^+ ions, a stabilizing complex is formed, which results in a superior quality of the prepared coating. Saltykova et al[58–60] prepared Ir coatings under the NaCl-KCl-CsCl system using DC and reversing currents, conducted an in-depth study on the coating properties and the influence of parameters, and found that the quality of the coatings was more significantly affected by the molten salt temperature, atmosphere conditions, and current density. At the temperature of 773–873 K, the structure of the prepared Ir coatings was dense and continuous. When the temperature continued to increase, the coating structure was dendritic, and the denseness deteriorated. With the increase in the cathodic current density, the growth rate of the coatings was increased linearly, and the surface roughness was also increased. The electrode had a smooth Ir coating under the condition of higher current density when the reversing current was used. Zhu et al[61–62] prepared Ir coatings on the surfaces of Mo, Re, and C/C composite matrices by ED technique at 600 °C in air, employing the chloride molten salt. By comparison, the Ir coatings on the Re matrix were dense and smooth, and they showed excellent bonding with the bond strength greater than 16 MPa. In contrast, Mo and C/C composite matrices were corroded by chlorides in the air, and the interface between Ir coating and matrix was poorly bonded and had low coating quality. Huang et al[56,63–64] investigated the failure mechanism of Ir coatings prepared by ED technique in high-temperature environment and found that the failure of Ir coatings is mainly due to the volatilization of its oxidation and the rapid diffusion of Re along the grain boundaries of Ir coatings, resulting in the optimal oxidation of grain boundaries and the formation of penetrating holes. The diffusion distance of Re in the coating determines the antioxidant property of the coating, and the longer the diffusion distance, the better the antioxidant property. In this regard, it is proposed that the high-temperature antioxidant performance of Re-based Ir coatings can be improved by preparing equiaxed crystalline structures with longer diffusion distances.

Table 1 comprehensively compares the process conditions and coating quality of different preparation techniques.

Although MS and DGP techniques can deposit high-quality coatings, their deposition rate is slow. Although ALD technique can deposit coatings on complex structures, its deposition rate is slow. The matrix material dramatically affects the coating quality, which restricts its application. At the same time, the platinum group metal coatings deposited by MS, DGP, and ALD techniques are thin, which restricts their high-temperature oxidation resistance to a certain extent. In contrast, CVD, MOCVD, and ED techniques have been more mature and are the commonly used technical means for the preparation of high-temperature antioxidant coatings of platinum group metals, especially ED technique, due to its low industrial cost. CVD, MOCVD, and ED techniques all show a better development prospect[65].

3 High-Temperature Oxidation Resistance of Platinum Group Metals

The high-temperature oxidation resistance of platinum group metals is discussed in terms of three main aspects: oxygen affinity, high temperature vapor pressure, and oxygen permeability. Table 2 shows the high-temperature oxidation resistance of platinum group metals[11,66].

The oxidation potential of platinum group metals is lower than that of other metals, and the dense platinum group metals are inert at room temperature, except for Ru and Os. The order of affinity for oxygen is as follows: Pt<Pd<Rh<Ir<Ru<Os. The oxidation resistance of platinum group metals is mainly related to the oxide film formed on their surfaces, preventing the severe corrosion at ambient or slightly higher temperatures in an oxygen-containing environment. Only when the temperature reaches the critical temperature, the surface oxides begin to dissociate and volatilize. In this case, the oxidative volatilization rate of platinum group metals is lower than that of most other high-temperature protective materials.

At high temperatures, the platinum group metals have low vapor pressures, as shown in Fig. 5[66]. Especially, Os, Ir, and Ru have the saturated vapor pressures of only 2.0×10^{-9}, 2.1×10^{-6}, and 1.0×10^{-5} Pa at 1600 °C, respectively[66]. Refractory metals have much higher vapor pressures than the platinum group metals at the same temperature. This also means that at

Table 1 Comparison of preparation techniques of high-temperature antioxidant platinum group metal coatings

Technique	Characteristic	Coating quality	Disadvantage
MOCVD	Controllable deposition rate and coating thickness; high deposition rate	Dense and highly uniform on complex-shaped parts	Expensive precursor; low utilization rate; complicated deposition atmosphere control
MS	High molding quality; unaffected by parts	Dense and smooth on complex-shaped parts	Low deposition rate; low yield; expensive target material; low bond strength
DGP	Strong sedimentation capacity; line-of-sight deposition	Dense and smooth on complex-shaped parts with good adhesion	Low deposition rate; expensive target material; complex equipment
ALD	Coating quality related to matrix element; self-limiting ability	Controllable coating thickness; dense and highly uniform on complex-shaped parts	Low deposition rate; thin coating thickness; restricted by the parts' elements
ED	Low cost; high deposition rate; high yield; simple operation	Dense and highly uniform on complex-shaped parts with high purity	Volatile and corrosive molten salt

Table 2   High-temperature oxidation resistance of platinum group metals[11,66]

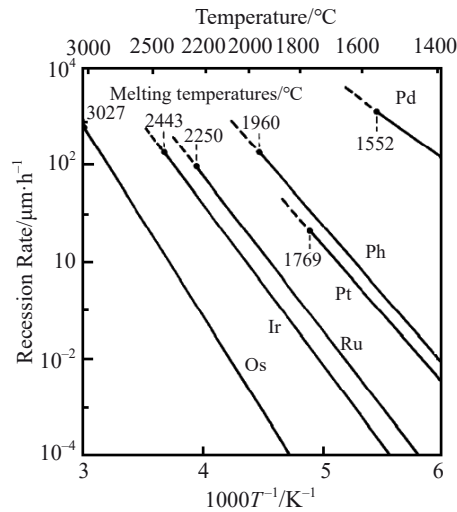| Metal	Ru	Rh	Pd	Os	Ir	Pt
Melting point/°C	2250	1960	1552	3030	2443	1769
Oxidation reaction temperature/°C	Room temperature	600	400	Room temperature	600	500
Oxidative product	RuO_2 RuO_4	RhO Rh_2O_3 Rh_2O	PdO	OsO_4	IrO_2 IrO_3	PtO PtO_2
Decomposition temperature of oxidation products/°C	-	1127	800	-	1100	900
Saturated vapor pressure at 1600 °C/Pa	1.0×10^{-5}	2.4×10^{-3}	-	2.0×10^{-9}	2.1×10^{-6}	1.0×10^{-1}

Note: the vapor pressure of palladium at 1552 °C is 4.2 Pa.

Fig.5 Relationships between vapor pressure and temperature of platinum group metals under high-vacuum environment[66]

Fig.6 Oxygen permeability of different materials as a function of temperature[67]

high temperatures, platinum group metals have lower thermal volatilization losses than the refractory metals. In the inert gas environment at pressure higher than 1000 Pa, the evaporation rate of platinum group metals is also decreased with the increase in gas pressure.

Oxygen permeability is crucial, considering the platinum group metals as high-temperature antioxidant coatings, as shown in Fig.6[67]. Except for Pd, the platinum group metals all have low oxygen permeability. Pd has a higher solid solubility to oxygen than other elements in the group, and it is permeable to oxygen when the temperature reaches 1400 °C. Ir has the lowest oxygen permeability among the platinum group elements, and its oxygen permeability is lower than 3.5×10^{-15} g· (cm·s) $^{-1}$ at 1075 – 2200 °C and oxygen partial pressure of 6666.1 Pa. The micron-thick Ir coating has the same oxygen barrier effect as the 1 mm-thick SiO_2 at 1800 °C[68]. Although it also exhibits low oxygen permeability, Pt reaches the limit value at 1400 °C. Thus, Pt metal can hardly satisfy the ultrahigh-vacuum service requirements.

Because Os and Ru have high oxidation rates and their oxides are toxic, they cannot be high-temperature antioxidant coatings. Pd permeability is high and cannot play a good antioxidant protection role for the matrix at high temperatures.
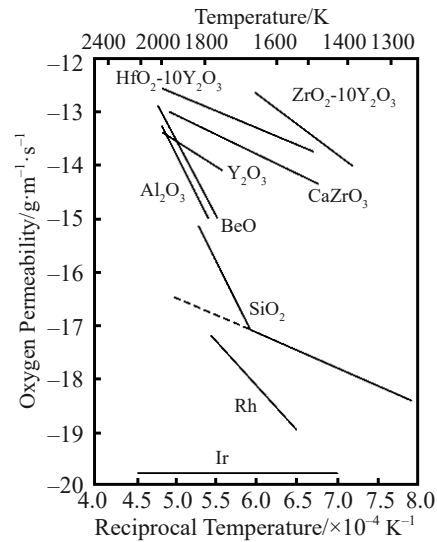
Ir, Rh, and Pt are currently desirable high-temperature antioxidant coating materials. Particularly, Ir, serving as a coating material as early as the 1980s[69], was used on Re/Ir thrust chambers with specific impulse levels as high as 322.2 s. The rocket chamber completed the operation at 2200 °C for 7 h while exhibiting excellent resistance to ablation[70–72].

Although platinum group metals exhibit excellent high-temperature oxidation resistance, they still have some drawbacks in ultrahigh-temperature environments. First of all, the oxide layer surface of the platinum group metals will dissociate at high temperatures, generating gaseous volatile oxides in the failure location to form a new oxide layer for matrix protection. By repeating this process, the coating is gradually thinned until it fails. The decomposition temperatures are shown in Table 2. As the temperature increases, the thinning rate of platinum group metals gradually accelerates. For example, the consumption rate of Ir coating is 3.9 μm/h at 1400 °C, while its volatilization rate is as high as 11 μm/h when the temperature is 2000 °C[73]. Secondly, the platinum group metals have high catalytic activity. In the high-temperature environment, the combination of active atomic state gases on the surface releases more heat, causing higher surface

temperature and exacerbating the depletion of platinum group metal coatings[74]. Therefore, there is a need to modify the platinum group metal coating to improve its performance.

In recent years, most studies on high-temperature oxidation-resistant platinum group metal coatings have focused on their modification. The essence of modification of platinum group metal coatings is to improve their oxygen barrier capacity and to reduce the catalytic activity while maintaining the original low oxygen permeability, low vapor pressure, and ultrahigh melting point under high-temperature conditions. Hence, the high-temperature antioxidant advantages can be maximized for high-temperature service requirements.

4 Alloying Modification of Platinum Group Metal Coatings

Currently, the modification of platinum group metal coating mainly involves the microstructure optimization, external ceramic coating, and alloying modification. Although the optimization of the structure can improve the quality of the coating, it still cannot change the oxidation consumption rate of the coating at high temperatures. The external ceramic layer can directly block the contact between the platinum group metal coating and the external environment. However, the ceramic layer is prone to internal stress due to solid-state phase transition, spalling, and loss of protective ability under high-temperature environments. Platinum group metal alloying modification is based on in-situ replacement. As the surface oxides of platinum group metal coating evaporate, the alloying elements create a new oxide ceramic layer over the surface to block oxygen intrusion. Platinum group metal-modified coatings commonly use elements Al, Hf, Zr, and Ta for optimization.

4.1 Alloying modification of Pt coatings

The concept of Pt-modified coatings was introduced in 1961, which is made of a mixture of Pt and other materials, and the performance of the Pt-modified coating is much better than that of the coating only containing Pt. Pt-Al coating is the most mature system of Pt-modified coatings[75]. On the one hand, Pt can increase the diffusion coefficient of Al, which makes it easier for Al to diffuse outward to form an Al_2O_3 protective layer[76–77]; on the other hand, Pt can reduce the interdiffusion of Al and refractory metal matrix, which improves the stability of the coatings[78–80]. Pt-Al coatings have good high-temperature antioxidant properties and excellent antioxidant ability in the oxidation environment at 1050 °C[81]. Yang et al[82] prepared dual-phase $PtAl_2$ coatings by low-activity-high-temperature aluminizing technique. The dual-phase $PtAl_2$ and the single PtAl coating were subjected to 300 oxidation cycles at 1100 °C. It was found that the phase transition of the single PtAl coating occurred under the oxygen-containing environment, which introduced a large amount of stress in the middle of the coating and the oxidized layer, resulting in wrinkles on the coating surface. In contrast, the $PtAl_2$ coating was significantly better than the single PtAl coating. Chong et al[83] explored the oxygen barrier ability of

$Pt_{82}Al_{12}M_6$ (*M*=Pt, Cr, Hf, and Ta) ternary system-modified alloy in high-temperature oxidation environment. After heat treatment under oxygen conditions at 1300 °C for 100 h, the cross-sectional morphologies were observed by electron probe X-ray microanalysis (EPMA), as shown in Fig. 7[83]. It was found that the oxidation resistance of $Pt_{82}Al_{12}Cr_6$ alloy at high temperature was superior to other alloys. Cr_2O_3 oxides are not formed in an oxygen atmosphere. The addition of Cr enhances the densification of protective layer of the Al_2O_3 oxides. The experiment results can fully correspond to the thermodynamic calculations, and it has a good development potential as a coating system. Currently, it is found that the service temperature of Pt-based binary or multisystem coatings is lower than 1400 °C, which cannot satisfy the service conditions of high hypersonic vehicles above 1800 °C. Problems, such as brittle fracture of PtAl system binary or poly-alloys at high temperatures, have also not been completely solved[84], which is related to the mismatch of thermal expansion coefficients between coatings and matrix materials. These problems restrict the application and development of Pt-based coatings as high-temperature thermal protective coatings. Thus, improving the high temperature protection and solving the problem of brittleness are the focus of future research on Pt-based modified coatings.

4.2 Alloying modification of Ir coatings

The study of the alloying modification of Ir coating is a key topic in the research of high-temperature oxidation-resistant coating, and Al, Hf, Zr, and Ta are commonly added elements in the current research. Table 3 summarizes the current progress of Ir-modified coatings[73,85–87].

Fig. 8[85] reveals the partial binary phase diagrams of the Ir-*M* systems. The high-temperature oxidation resistance of Ir-Al system coatings is good, and the dense Al_2O_3 oxide layer on the surface achieves the primary purpose of thermal protection. Lee[88] and Hill[89] et al found that when the Al content is lower than 55wt%, there are particular pores in the Al_2O_3 protective layer, and the protective effect is weak. Chou[90], Zhu[91], and Ai[92] et al demonstrated that when the Al content reaches a certain threshold, Ir-Al alloys have an $Ir-Al_{2.7(3)}$/Ir-Al bilayer structure, which is capable of attaching to the surface of the Ir coating with good interfacial bonding. In plasma wind tunnel tests, the surface temperature of Ir-Al was maintained at 1520 °C under heat flow density of 3 MW/m^2, while the surface temperature of pure Ir already reached 2494 °C under heat flow density of 2.03 MW/m^2[74]. Adding Al can reduce the catalytic activity and improve the overall high-temperature oxidation resistance of the Ir coatings. However, $Ir-Al_{2.7(3)}$ has a low melting point, the oxide protective layer melts and fails above 2000 °C, and the coating depletion is accelerated[74,93]. Thus, the system cannot meet the development needs at higher temperatures. Similar to the case in Ir-Al alloy system, the content of the modifying elements in the Ir-Hf and Ir-Zr systems also needs to reach a certain threshold to form the dense oxide layer[88]. Hf (2810 °C) and Zr (2610 °C) are similar, and their oxidation temperature is both higher than that of Al (2050 °C). Therefore, they can
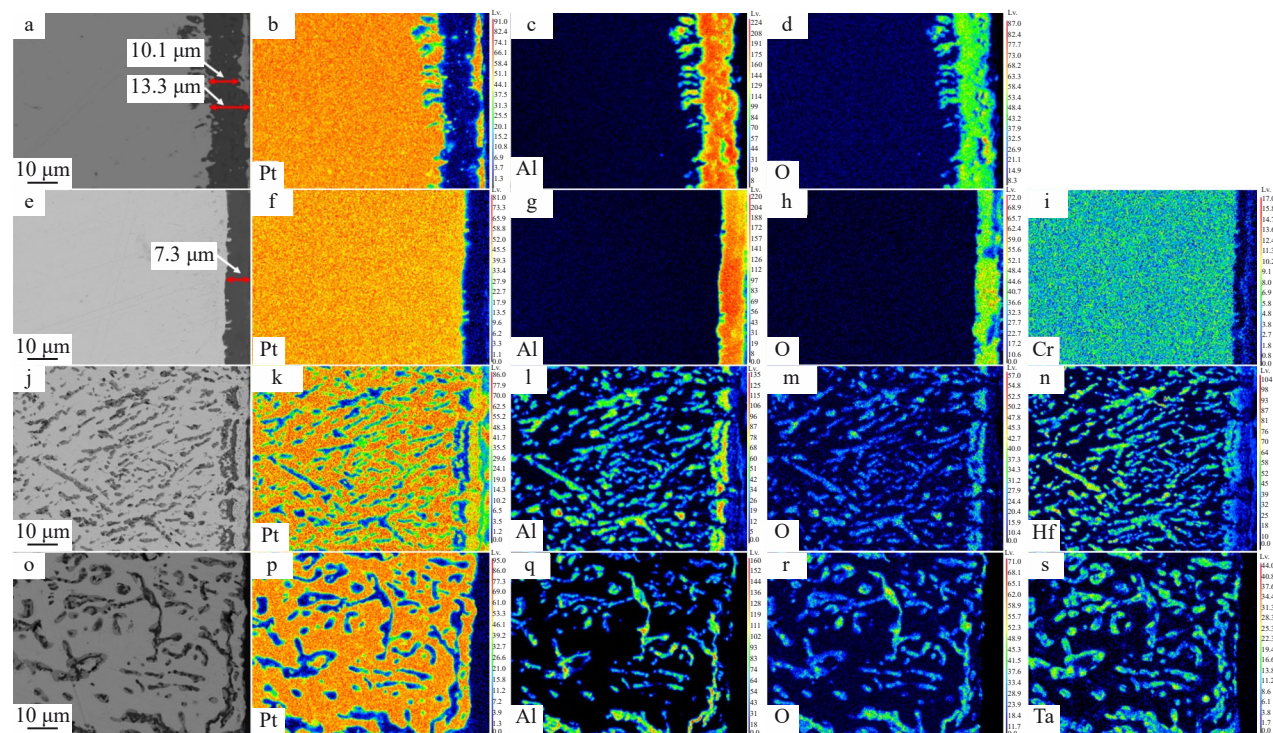
Fig.7 Cross-sectional morphologies (a, e, j, o) and EPMA element distributions (b–d, f–i, k–n, p–s) of $Pt_{82}Al_{12}M_6$ alloys after oxidation in air at 1300 °C for 100 h[83]: (a–d) without the third metal element; (e–i) M=Cr; (j–n) M=Hf; (o–s) M=Ta

Table 3 Comparison of high-temperature oxidation resistance of Ir and Ir-modified binary system coatings[73,85-87]

System	Protective oxide	Ultimate temperature/°C	Ultimate heat flow/MW·m^{-2}	Failure mode
Ir	-	2446	1.6	Melting, oxidizing, and volatilizing
Ir-Hf	HfO_2	2268	6.6	Ir melting
Ir-Al	Al_2O_3	2050	3.5	Al_2O_3 melting
Ir-Zr	ZrO_2	2320	6.1	Ir melting
Ir-Ta	Ta_2O_5	1800	2.5	Ta_2O_5 melting or broken ZrO_2

resist high temperatures above 2200 °C in the atmosphere containing oxygen. Zhang[94] and Li[95] et al modified Ir coatings by powder solid infiltration method and prepared coatings of Ir-Hf and Ir-Zr systems with a multilayer structure, which also showed better antioxidant properties, as shown in Fig.9[86–87]. The ultimate heat flow density of the Ir-Hf system in the wind tunnel test was 6.6 MW/m^2. The surface temperature was maintained at 2200 °C, and the service life was higher than 400 s[86]. The ultimate heat flow density of the Ir-Zr system is 6.1 MW/m^2. The surface temperature is maintained at 2240 °C with a service life of about 100 s[87]. However, the mechanical properties of ZrO_2 are inferior, compared with those of HfO_2, which is prone to rupture, leading to coating failure[95]. Ir-Ta and Ir-Y alloy coatings are less effective and fail under the heat flow density of less than 3.5 MW/m$^{2[73]}$. Comparing the results in Ref.[95–96], under the same environment, the more the intermetallic compounds in the alloying-modified Ir coating, the better the oxidation resistance of the coating.

According to related reports, adding more elements to form ternary or even multivariate Ir coatings can enhance the thermodynamic properties and structural stability of coatings[97]. However, the more the added elements, the lower the service temperature of the coatings. For example, the protective temperatures of Ir-Al-Hf and Ir-Al-Zr systems are 1890 (Al_2O_3-HfO_2) and 1860 (Al_2O_3-ZrO_2) °C, respectively, which are much lower than those of the binary systems[98], such as 2050 (Al_2O_3), 2680 (ZrO_2), and 2810 (HfO_2) °C. Adding elements can provide good protective effect in service below 1800 °C, but the protective effect above 1800 °C is much worse than that of the binary system coatings. Different coating systems of Ir coatings can be selected according to their service conditions.

4.3 Alloying modification of other platinum group metal coatings

Due to the high price of platinum group metals and their high catalytic activity, except for Pt and Ir, there are relatively few research reports on the modification of coating of platinum group metals, and most of them discuss the catalysis, separation, and other techniques[99–102]. Al, as an additive element, is widely used in alloying modifications of platinum
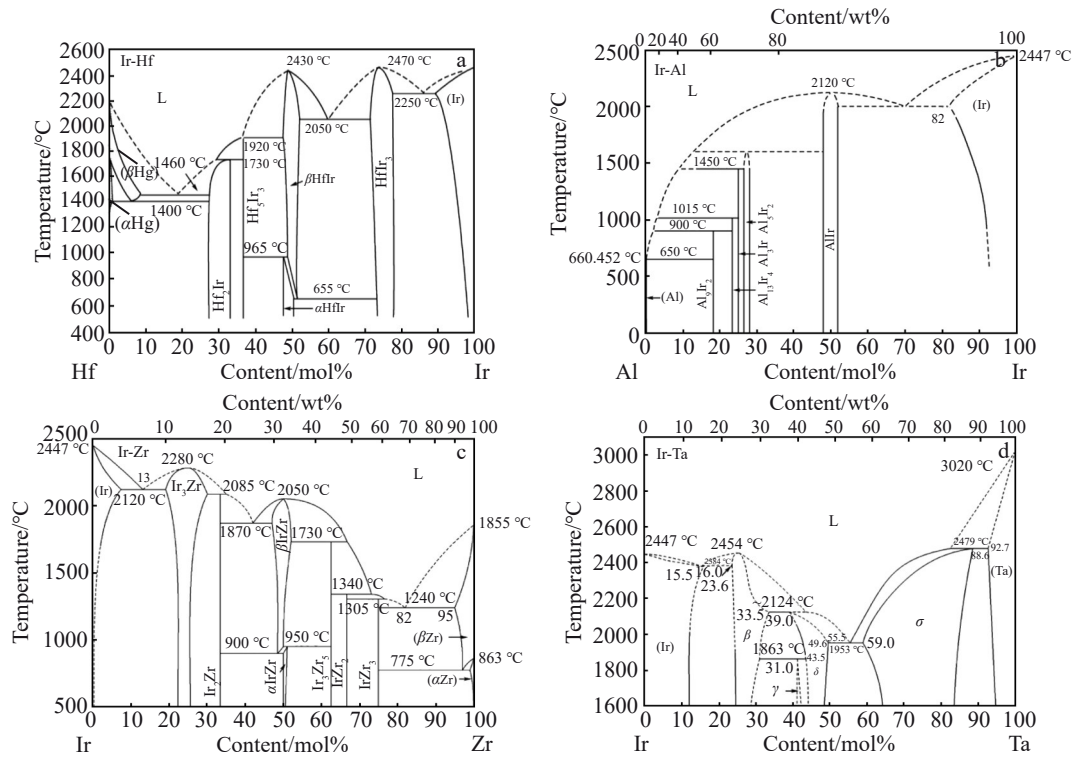
Fig.8 Partial binary phase diagrams of Ir-*M* systems[85]: (a) Ir-Hf; (b) Ir-Al; (c) Ir-Zr; (d) Ir-Ta
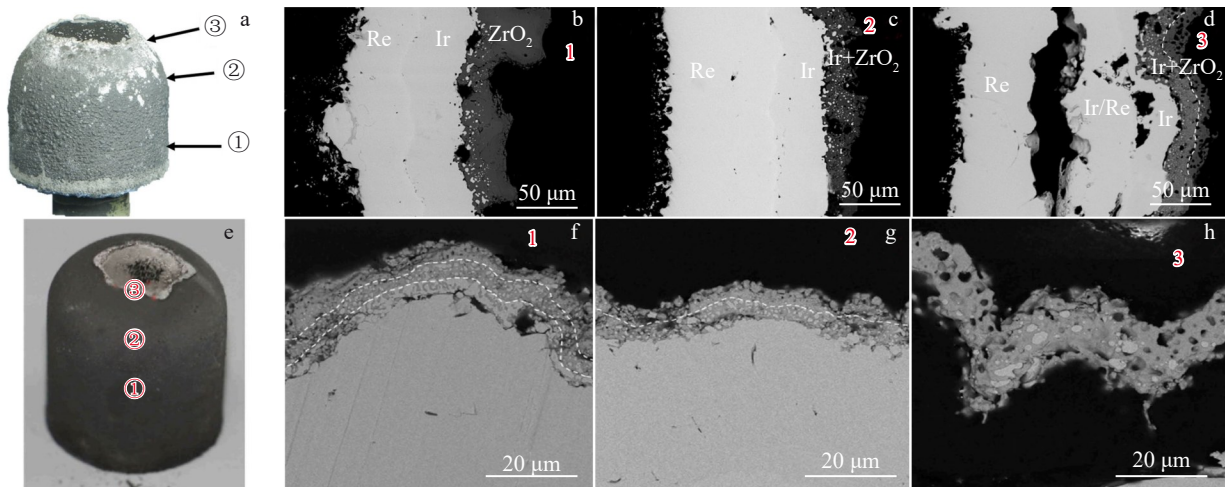

Fig.9 Temperature measurement points (a, e) and corresponding SEM microstructures (b−d, f−h) of Ir-Zr alloy coating (a−d) and Ir-Hr alloy coating (e−h) of plasma wind tunnel during ablation test[86−87]

group metal coatings. Pd-Al coatings have similar structures to Pt-Al coatings. Some studies have shown that the thermal stability and mechanical properties of Pd-Al coatings are better than those of Pt-Al coatings[103–104]. However, the related studies are not profound, and the enhancement is related to the relatively high oxygen permeability of Pd.

The research about Rh for high-temperature oxidation resistance mainly focuses on the modified alloys. Rh-Pt[105–108] and Rh-Ir[109–111] alloys have excellent high-temperature mechanical properties and antioxidant ability, which are always the research hotspot in ultrahigh-temperature structural materials. Powder metallurgy, spray molding, and internal oxidation are usually used to prepare Rh-Pt and Rh-Ir alloys. As a coating system, its preparation is complicated. Studies on Rh-Pt and Rh-Ir coatings are rarely reported. In addition, Rh, as the most expensive element in the platinum group metals, has a lower melting point (1964 ℃), inferior oxygen permeation resistance, and low vapor pressure, which makes it less promising than Ir-based coatings for aerospace and weapon applications.

5 Conclusions and Prospects

Platinum group metal coatings, as high-temperature antioxidant coatings, have been widely noticed and applied in

the field of high-temperature antioxidants due to their excellent properties and characteristics.

1) As the common materials for high-temperature antioxidant coatings, platinum group metal coatings are prepared by diverse and relatively mature techniques. However, the bonding problem between the coating and matrix, the oxidation problem at the grain boundary, and the unclear microstructure growth in the preparation process still need further exploration and consideration. Considering the high cost of platinum group metals and the requirements of preparation techniques, molten salt ED is the most suitable preparation technique. At present, the preparation of Ir coatings by molten salt ED is relatively mature, and how to promote the application of the molten salt ED technique to the preparation of other platinum group metal coatings requires more in-depth research.

2) Compared with the platinum group metal elements of high-temperature oxidation resistance, the oxidation rate of Os and Ru is high, and their oxides are toxic. Pd has a relatively high oxygen permeability. Os, Ru, and Pd cannot be used as high-temperature antioxidant coating materials. Pt is permeable to oxygen at 1400 °C. To satisfy the service conditions of ultrahigh-speed vehicles, only Ir and Rh can be used. The melting point and resistance to oxygen permeability of Rh are lower than those of Ir, and the price of Rh is higher than that of Ir. Ir is currently the ideal high-temperature antioxidant coating material for hot-end components of hypersonic aircraft.

3) Alloying modification is one of the effective methods to improve the high-temperature oxidation resistance of platinum group metal coatings. Currently, Hf, Al, and Zr are the commonly used additive elements for coating modification. Through the in-situ generation of dense oxides, the coating plays an inevitable role in enhancing the antioxidant performance of the coating. Concerning the multisystem modification of platinum group metal coatings, although the problems of coatings modified by single element can be reduced, the melting point of the mixed oxides is lower than that of single-element modified coatings (Ir-Al-Hf). Therefore, the multifunctional modification of the platinum group metal coatings still needs investigation to find a more suitable modification technique to achieve a synergistic effect.

4) Multicomponent and multilayer structure coating designs are the vital development directions for platinum group metal coatings. Platinum group metals are expensive, and designing coating structures through calculations can result in significant cost savings. Research and development of new preparation process techniques or a combination of various preparation methods should be conducted, providing more possibilities for application in aerospace and defense fields.

References

1　Peters A B, Zhang D, Chen S *et al*. *Nature Communications*[J], 2024, 15(1): 3328

2　Ding Y B, Yue X K, Chen G S *et al*. *Chinese Journal of Aeronautics*[J], 2022, 35(7): 1

3　Barcohen Y. *High Temperature Materials and Mechanisms*[M]. Beijing: Aviation Industry Press, 2019: 4

4　Kolek A N, Cooper S R, Behler K D *et al*. *International Journal of Applied Ceramic Technique*[J], 2024, 21(2): 1010

5　Kong J A, Zhang Y L, Gai W H *et al*. *Corrosion Science*[J], 2022, 205: 110426

6　Zhang B W, Zhong F G, Qiu X C *et al*. *Journal of Solid State Chemistry*[J], 2024, 329: 124384

7　Zhong L, Guo L J, Li Y Y *et al*. *Materials Characterization*[J], 2023, 198: 112722

8　Beck K, Ulrich A S, Czerny A K *et al*. *Surface and Coatings Technique*[J], 2024, 476: 130205

9　Zhang Shihong, Wang Qimin, Zheng Junbian. *Principle and Application of Vapor Deposition Technique*[M]. Beijing: Metallurgical Industry Press, 2020: 93 (in Chinese)

10　Cai Hongzhong, Chen Li, Wei Yan *et al*. *Rare Metal Materials and Engineering*[J], 2010, 39(2): 209 (in Chinese)

11　Hu Changyi, Liu Shijie. *New Materials of Precious Metals*[M]. Changsha: Central South University Press, 2015: 127 (in Chinese)

12　Muhammad A E, Mahedi H M, Tamanna I *et al*. *ACS Applied Electronic Materials*[J], 2019, 1(3): 417

13　Garcia V, Goto T. *Materials Transactions*[J], 2003, 44(9): 1717

14　Reed B D, Dickerson R. *1995 JANNAF Propulsion Meeting*[C]. New York: National Aeronautics and Space Administration, 1995: 1

15　Harding J T, Kazaroff J M, Appel M A. *Surface Modification Techniques II*[C]. Texas: NASA Technical Memorandum, 1988: 1

16　Goto T, Vargas R, Hirai T. *Journal de Physique IV*[J], 1993, 3(3): 297

17　Hu Changyi, Dai Jiaoyan, Fang Ying *et al*. *Rare Metal Materials and Engineering*[J], 2006, 35(4): 546 (in Chinese)

18　Hu C Y, Wan J G, Dai J Y. *Platinum Metals Review*[J], 2005, 49(2): 70

19　Goto T, Vargas J R, Hirai T. *Materials Transactions JIM*[J], 2007, 40(3): 09

20　Maury F, Senocq F. *Surface and Coatings Technique*[J], 2003, 163–164: 208

21　Gelfond N V, Morozova N B, Semyannikov P P *et al*. *Journal of Structural Chemistry*[J], 2012, 53(4): 715

22　Lasse J, Michael F, Myeongwhun P *et al*. *Organometallics*[J], 2017, 36(12): 2331

23　Dorovskikh S I, Krisyuk V V, Mirzaeva I V *et al*. *Polyhedron*[J], 2020, 182: 114475

24　Zharkova G I, Baidina I A, Smolentsev A I *et al*. *Journal of Structural Chemistry*[J], 2017, 58(5): 970

25　Dorovskikh S I, Karakovskaya K I, Vikulova E S *et al*. *Journal of Structural Chemistry*[J], 2022, 63(7): 1134

26　Nils B, Wree J L, Zanders D *et al*. *ACS Applied Materials and Interfaces*[J], 2022, 14(46): 2149

27　Elers K E, Blomberg T, Peussa M *et al*. *Chemical Vapor Deposition*[J], 2006, 12(1): 13

28　Wang C D, Hu L H, Lin Y Y *et al*. *Journal of Physics D: Applied*

Physics[J], 2017, 50(41): 415301

29 Aaltonen T, Ritala M, Leskelä M. *Electrochemical and Solid-State Letters*[J], 2006, 8(8): C99

30 Hämäläinen J, Sajavaara T, Puukilainen E *et al. Chemistry of Materials*[J], 2012, 24(1): 55

31 Schmitt P, Paul P, Li W *et al. Coatings*[J], 2023, 13(4): 787

32 Gao H J, Xiong Y Q, Zhang K F *et al. Physica B: Condensed Matter*[J], 2022, 630: 413601

33 Gao H J, Xiong Y Q, Liu X L *et al. Applied Surface Science*[J], 2016, 389(1): 211

34 Hong K C, Kim H, Jeon J *et al. The Journal of Physical Chemistry Letters*[J], 2023, 14(28): 6486

35 Park N, Kim M, Kim Y *et al. Chemistry of Materials*[J], 2022, 34(4): 1533

36 Xu Zhong. *Plasma Surface Metallurgy with Double Glow Discharge Technique*[M]. Beijing: Science Press, 2017: 33 (in Chinese)

37 Xu Z, Wu H, Huang J *et al. AIP Advances*[J], 2023, 13(9): 095308

38 Wu W P, Chen Z F. *Acta Metallurgica Sinica* (*English Letters*)[J], 2012, 25(6): 469

39 Zhu X B, Dang B, Li F K *et al. Materials Research Express*[J], 2021, 8(1): 016411

40 Chen Zhaofeng, Wang Bingliang, Zhang Pingze *et al. Journal of Nanjing University* (*Natural Sciences*)[J], 2009, 45(2): 234 (in Chinese)

41 Wu W P, Chen Z F, Liu Y. *Plasma Science and Technique*[J], 2012, 14(10): 909

42 Wu W P, Lin X, Chen Z F *et al. Plasma Chemistry and Plasma Processing*[J], 2011, 31(3): 465

43 Wang L B, Chen Z F, Zhang Y. *International Journal of Refractory Metals and Hard Materials*[J], 2008, 27(3): 590

44 Chen Z F, Wu W P, Cheng H *et al. Acta Astronautica*[J], 2010, 66(5–6): 682

45 Zhang Z W, Xu Z H, Wang J M *et al. Journal of Materials Engineering and Performance*[J], 2012, 21(10): 2085

46 Wu W P, Chen Z F, Cong X N. *Surface Engineering*[J], 2012, 28(8): 627

47 Wu W P, Chen Z F. *Journal of Adhesion Science and Technique*[J], 2012, 26(10–11): 1705

48 Marot L, Temmerman G D, Oelhafen P *et al. The Review of Scientific Instruments*[J], 2007, 78(10): 103507

49 Khoa T D k, Horii S, Horita S. *Thin Solid Films*[J], 2002, 419(1–2): 88

50 Mumtaz K, Echigoya J, Hirai T *et al. Materials Science and Engineering*[J], 1993, 167(1–2): 187

51 Mumtaz K, Echigoya J, Hirai T *et al. Journal of Materials Science Letters*[J], 1993, 12(18): 1411

52 El-Khakani M A, Chaker M, Le Drogoff B. *Journal of Vacuum Science and Technique A*[J], 1998, 16(2): 885

53 Huo X D, Zhou G D, Feng M Y *et al. Results in Physics*[J],

2021, 30: 104878

54 Bai Shuxin, Zhu Li'an, Zhang Hong *et al. Rare Metal Materials and Engineering*[J], 2015, 44(7): 1815 (in Chinese)

55 Qian J G, Zhao T. *Transactions of Nonferrous Metals Society of China*[J], 2012, 22(11): 2855

56 Huang Yongle. *Electrochemical Reduction Mechanism Structure-Control and Oxidation Resistance of Ir Coating Prepared by Electrodeposition from Molten Salts*[D]. Changsha: National University of Defense Technique, 2017 (in Chinese)

57 Zhu Li'an. *Preparation and Properties of High Temperature Ir/Re Coating*[D]. Changsha: National University of Defense Technique, 2014 (in Chinese)

58 Saltykova N A, Kotovskii S N, Portnyagin O V *et al. Soviet Electrochemistry*[J], 1990, 26(3): 302

59 Saltykova N A, Pechorskaya L S, Baraboshkin A N *et al. Soviet Electrochemistry*[J], 1986, 22(5): 545

60 Saltykova N A, Baraboshkin A N, Korovenkov A P. *Elektrokhimiya*[J], 1985, 21(9): 1159

61 Zhu L A, Bai S X, Zhang H. *Surface and Coatings Technique*[J], 2011, 206(6): 1351

62 Zhu L A, Bai S X, Zhang H *et al. Physics Procedia*[J], 2013, 50: 238

63 Huang Y L, Bai S X, Zhang H *et al. Surface and Coatings Technique*[J], 2017, 322: 76

64 Huang Y L, Bai S X, Zhang H *et al. Journal of Electroanalytical Chemistry*[J], 2017, 791: 138

65 Anderson D, Pencil E, Liou L *et al. Joint Propulsion Conference 2009*[C]. New York: NASA Technical Reports Server, 2009

66 Jehn H. *Journal of the Less Common Metals*[J], 1984, 100(C): 321

67 Wang Xin, Zhang Ping, Hu Zhenfeng *et al. Materials Protection*[J], 2022, 55(3): 107 (in Chinese)

68 Hosoda H, Miyazaki S, Hanada S. *Intermetallics*[J], 2000, 8(9–11): 1081

69 Criscione J M, Smith A W, Volk H F. *AIAA Journal*[J], 1966, 4(10): 1791

70 Schneider S J. *Acta Astronautica*[J], 1992, 28: 115

71 Fortini A, Tuffias R. *35th Joint Propulsion Conference and Exhibit*[C]. Los Angeles: AIAA, 1999

72 Stechman C, Woll P, Fuller R *et al. 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*[C]. Las Vegas: AIAA, 2000

73 Zhang Kaili. *Design, Preparation and Thermal Protection Mechanism of Ir-X Coatings*[D]. Changsha: National University of Defense Technique, 2020 (in Chinese)

74 Zhang K L, Bai S X, Zhu L *et al. Surface and Coatings Technique*[J], 2019, 358: 371

75 Bose S. *High Temperature Coatings Second Edition*[M]. Oxford: Butterworth-Heinemann, 2018: 113

76 Pint B A. *Surface and Coatings Technique*[J], 2005, 188–189: 71

77 Oskay C, Christian M, Murakami H. *Materials at High Temperatures*[J], 2019, 36(5): 404

78 Liu Gang. *High Temperature Oxidation Behavior of Single Aluminizing Coating and Platinum Aluminum Coating*[D]. Shengyang: Institute of Metal Research, Chinese Academy of Sciences, 2000 (in Chinese)

79 Krishna G R, Das D K, Singh V *et al. Materials Science and Engineering*[J], 1998, 251(1): 40

80 Shirvani K, Rashidghamat A. *Oxidation of Metals*[J], 2016, 85(1–2): 75

81 Koochaki-Abkenar A, Malekan A, Bozorg M *et al. Metals and Materials International*[J], 2024, 30(9): 2466

82 Yang Y F, Ren S X, Ren P *et al. Journal of Alloys and Compounds*[J], 2022, 911: 164978

83 Chong X Y, Yu W, Liang Y X *et al. Journal of Materials Informatics*[J], 2023, 3(4): 21

84 Barjesteh M M, Madar K Z, Abbasi S M *et al. Journal of Central South University*[J], 2022, 29(1): 43

85 Dai Yongnian. *Binary Alloy Phase Diagrams*[M]. Beijing: Science Press, 2009: 69 (in Chinese)

86 Li F Y, Zhu L A, Zhang K L *et al. Materials Today Communications*[J], 2024, 39: 109288

87 Li F Y, Zhu L A, Zhang K L *et al. Journal of Materials Research and Technique*[J], 2024, 28: 4428

88 Lee K N, Worrell W L. *Oxidation of Metals*[J], 1989, 32(5–6): 357

89 Hill P J, Cornish L A, Witcomb M J. *Journal of Alloys and Compounds*[J], 1998, 280(1–2): 240

90 Chou T C. *Journal of Materials Research*[J], 1990, 5(2): 378

91 Zhu L A, Du G B, Bai S X *et al. Corrosion Science*[J], 2017, 123(15): 328

92 Ai Y L, Bai S X, Zhu L A *et al. Surface and Coatings Technique*[J], 2019, 367(15): 302

93 Du Guangbao. *Study on Prepration and High Temperature Oxidation Behavior of Aluminizing Iridium Coating*[D]. Changsha: National University of Defense Technique, 2016 (in Chinese)

94 Zhang K L, Zhu L A, Bai S X *et al. Journal of Alloys and Compounds*[J], 2020, 818: 152829

95 Li F Y, Zhu L A, Zhang K L *et al. Surface and Coatings Technique*[J], 2023, 466: 129640

96 Chen Z F, Wu W P, Cong X N. *Journal of Materials Science and Technique*[J], 2014, 30(3): 268

97 Sha J B, Yamabe-Mitarai Y. *Intermetallics*[J], 2013, 41: 1

98 Ai Yuanlin. *Study on Preparation, Oxidation Behavior and Ablation Behavior of Ir-Al-X Coating*[D]. Changsha: National University of Defense Technique, 2018 (in Chinese)

99 Cardinal S, Pelletier J, Kato H. *Rare Metal Materials and Engineering*[J], 2024, 53(1): 1

100 Zhu Lixian, He Junjie, Zhang Renyin *et al. Rare Metal Materials and Engineering*[J], 2023, 52(11): 3931 (in Chinese)

101 Li Hongpeng, Jiang Yunbo, He Jianyun *et al. Rare Metal Materials and Engineering*[J], 2023, 52(4): 1345 (in Chinese)

102 Li Guangzhong, Wang Hao, Li Yaning *et al. Rare Metal Materials and Engineering*[J], 2023, 52(7): 2505 (in Chinese)

103 Maryana Z Y, Jan S, Tadeusz G. *Archives of Metallurgy and Materials*[J], 2012, 57(2): 503

104 Romanowska J, Morgiel J, Kolek Ł *et al. Archives of Civil and Mechanical Engineering*[J], 2018, 18(4): 1421

105 Liu Y, Jiang H C, Zhao X H *et al. Ceramics International*[J], 2022, 48(22): 33943

106 Tian M, Hu C, Cai H *et al. Materials Science and Engineering A*[J], 2020, 797: 139966

107 Krstic V, Marjanovic S, Trumic B *et al. Archives of Metallurgy and Materials*[J], 2015, 60(2): 643

108 Trumić B, Gomidželović L, Marjanovič S *et al. Materials Testing*[J], 2013, 55(1): 38

109 Yusenko K V, Khandarkhaeva S, Fedotenko T *et al. Journal of Alloys and Compounds*[J], 2019, 788: 212

110 Pan Xindong, Wei Yan, Cai Hongzhong *et al. Acta Physica Sinica*[J], 2016, 65(15): 168 (in Chinese)

111 Cai Hongzhong, Yi Jianhong, Wei Yan *et al. Precious Metals*[J], 2016, 37(S1): 28 (in Chinese)

高温抗氧化铂族金属涂层的研究现状及展望

丁晨曦[1]，刘忠宇[1,2]，方　镇[1]，王浩旭[1]，吕　镖[1,3]，胡振峰[1]

(1. 军事科学院 国防科技创新研究院，北京 100071)

(2. 沈阳理工大学 材料科学与工程学院，辽宁 沈阳 110159)

(3. 中国人民解放军63723部队，山西 忻州 036300)

摘　要：铂族金属具有熔点高、耐腐蚀性强、化学性质稳定以及在高温含氧环境下氧渗透率低等特点，作为热防护涂层材料已在航空航天领域获得重要应用，并在高超声速飞行器热端部件防护等前沿军事领域应用前景极大。本文综述了高温抗氧化铂族金属涂层的最新研究进展，包括涂层制备技术、氧化失效及合金化改性。概述了当前铂族金属涂层的主要制备技术，总结并对比了现有各种制备技术之间的优劣情况。着重分析并总结了单一铂族金属涂层在高温含氧环境中的本征特性、失效形式及失效机制。在此基础上，梳理并指出了铂族金属合金化改性的必要性、主要方式及主要成果。最后，对高温抗氧化铂族金属涂层的未来发展进行了探讨及展望。

关键词：铂族金属涂层；制备技术；高温；抗氧化；合金化改性