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ARTICLE

Failure Modes of High Temperature Protective Coating for Aircraft APU Turbine Guide Vanes

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Abstract: The structural characteristics and thermal protection mechanism of a certain type of auxiliary power unit (APU) turbine guide vane in service were analyzed by scanning electron microscope (SEM) and energy dispersive analyzer (EDS). Then, the thickness variation and failure mode of the high temperature protective coating after removal from aircraft were investigated. The results show that there are two different coating structures in the aircraft APU guide vanes: aluminized coating+MCrAlY coating and mono aluminized coating. The MCrAlY coating thickness of the scrapped APU guide vane components increases first and then decreases from the area of trailing edge to the pressure side and then to the leading edge. Affected by the configuration and the service environment of APU guide vanes, the coatings at the trailing edge and pressure side present an oxidation-predominant damage mode. The oxidation degree of the coating on the trailing edge is more serious, while the closer the pressure-side region to the leading edge, the less severe the oxidative damage. However, due to the coupling effect of CMAS (CaO, MgO, Al_2O_3, SiO_2) corrosion and high temperature oxidation, the damage to the coating at the leading edge of vanes is the most serious.

Key words: turbine guide vane; high temperature protective coating; MCrAlY; high temperature oxidation; CMAS corrosion

With the development of the aviation industry, the requirements for the thrust-to-weight ratio is increasing. In order to ensure the high thrust-to-weight ratio and reliability of aero-engine, superalloys are widely used in the new generation of aero-engine. Nickel-based superalloys are the preferred materials for hot-section components of aero-engine due to their good microstructure and creep resistance [1]. However, the general working temperature of currently used nickel-based superalloys can only reach 1200 °C, and the further improvement is very restricted. At present, the turbine inlet temperature (TIT) of commercial and civil aircraft engines can reach 1500 °C, and the inlet temperature of military engines can reach 1700 °C or even higher, and these temperature values are already well above the melting point of most metal materials, including nickel-based alloys. Therefore, how to use advanced materials with better heat resistance to ensure reliable and efficient operation as hot-section components in high temperature working environment has always been a popular issue in academic and engineering research. For turbine vanes or blades, the durability and reliability can be improved by the following three methods[2–5]: (1) advanced materials to improve the temperature resistance of hot-section components, such as directional crystallization and single crystal superalloys; (2) efficient cooling technology; (3) high temperature protective coating technology. Among them, the most efficient and economic method is high-temperature protective coating technology. As a material for heat insulation and protection, high-temperature protective coating is widely used in advanced steam turbine systems, aircraft engine core components, and other hot-section components[6–8]. It can not only protect the substrate from thermal corrosion and high temperature oxidation, but also improve the thermal efficiency of the hot-section components, and solve the problems that cannot be solved by high temperature resistance[9–10]. As part of aero-engine hot-section components, turbine guide vanes produce thermal fatigue

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when they are exposed to harsh environment during use and operation. Harsh environment usually includes high temperature and pressure, sudden temperature changes (cold-heat cycle), high-pressure gas scouring, gas impurity corrosion, and high-speed particle impact. CMAS (CaO, MgO, Al_2O_3, SiO_2) corrosion and high-temperature oxidation corrosion caused by harsh environment are the main factors for the failure of high temperature protective coatings of aero-engine turbine guide vanes[11–12]. The failure of the high temperature protective coating causes the vane to lose its surface thermal protection, thereby causing the loss of system function. Therefore, it is of great theoretical value and engineering application significance to study the damage mode and failure mechanism of high temperature protective coating on aero-engine turbine guide vanes in actual working conditions. It is also of great value to ensure the safety and stability of aircraft and engines to improve the reliability and maintainability of engine hot-section components.

Researchers have obtained some results on the damage and failure mechanism of aero-engine vanes/blades as well as their high temperature thermal protective coatings. Qian et al[13] studied the failure of turbine guide vanes and found that the main cause of cracks is the local over temperature caused by the uneven temperature field. The research of Qin et al[14] also proved that thermal fatigue can cause cracking on the gas film hole edge of the high-pressure turbine guide vane, and the early fatigue cracking is related to the sharp gas film hole orifice edge. Duong et al[15] discussed a specific auxiliary power unit (APU) guide vane failure mode involving aero-mechanical and control feedback interaction, which is the result of multiple factors such as uneven wear, blade resonance, foreign matter contamination, and APU shutdown. Most of the related studies focus on the analysis of the local damage area, but there are relatively few researches on the difference in the failure mode of the overall state of the guide vane or the variation of temperature field in different areas.

In this study, the scrapped components of the first-stage guide vanes of an APU high-pressure turbine actually operated by an airplane was taken as the research object. The change trend of different failure modes and damage mechanisms were analyzed at the leading edge, trailing edge and pressure side of this type of guide vane, so as to obtain the typical failure modes of high temperature protective coatings in different areas of APU turbine guide vane, which provides a research basis for improving the overall service life and optimizing the guide vane structure.

1 Experiment

The failure components of the first-stage guide vane of APU high-pressure turbine of aircraft actually operated by airlines were taken as the research object. The vane configuration and division are shown in Fig. 1. The substrate of the vane was a nickel-based superalloy, and the surface of the substrate was covered with high temperature protective coating. The leading edge, trailing edge and the pressure side of the coating were aluminized+MCrAlY structure, namely Al-Si co-infiltration coating (50 μm)+MCrAlY metal coating (80 μm) prepared by EB-PVD process, and the vane's suction side was a single Al-Si coating (50 μm).

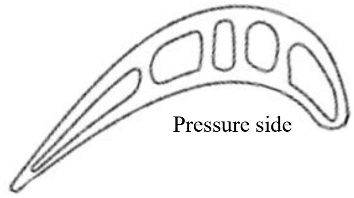

Fig.1 Schematic diagram of a certain type of APU high-pressure turbine guide vane

After the overall cutting of the guide vane, the cold inlay method was used to prepare the test specimens. The Sigma 300 field emission scanning electron microscope (SEM) produced by Zeiss Company in Germany was used to observe the microstructure of the guide vane in different cross-sectional areas, and the chemical composition inside the coating was analyzed by energy dispersive spectrometer (EDS).

2 Results and Discussion

2.1 Structure and thermal protection mechanism of high temperature protective coating for turbine guide vanes

As mentioned above, there are two different high temperature protective coating structures in aircraft APU guide vanes. The coatings in the areas of the vane's leading edge, trailing edge, and pressure side are aluminized+MCrAlY structure, named as Al-Si coating (original thickness of about 50 μm)+MCrAlY metal coating (original thickness of about 80 μm) prepared by EB-PVD (Fig.2a); while the vane's suction side is a single Al-Si coating (50 μm), as shown in Fig.2b. It should be noted that the coating thickness presented in Fig. 2 is not the original thickness of the as-prepared coating, because the guide vane coating may be subjected to high temperature oxidation, high temperature thermal corrosion, thermal shock and particle impact under the working condition of the APU. The thickness of the coating decreases due to the damage such as corrosion and high temperature ablation, and the thickness of the aluminized coating may increase due to the interdiffusion of elements between the coating and the substrate, thus forming a Ni-Al interdiffusion layer, as shown in Fig.2b.

Aluminized coatings are widely used in aero-engine turbine guide vanes due to the superior properties of aluminum in many antioxidant elements[16]. Aluminum reacts with O at high temperature to form stable Al_2O_3, which has a good protective effect on the substrate material[17]. The aluminized coating of the guide vane will undergo a high temperature diffusion reaction during the service process. As shown in Fig. 2b, the high temperature diffusion will cause the Al element and the Ni element in the substrate to diffuse into each other to form a

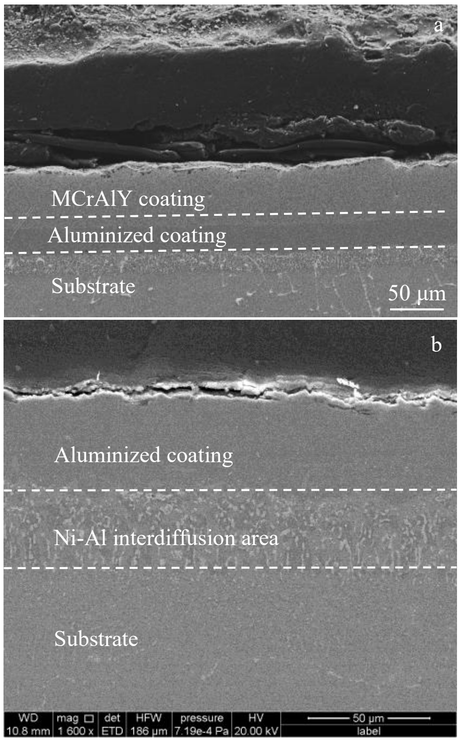

Fig.2 Aluminized coating+MCrAlY coating structure (a) and aluminized coating (b)

Ni-Al co-infiltration layer. The high degree of interdiffusion between the two layers leads to the reduction of Al element on the surface of the substrate, which will affect the thermal insulation effect[18], while the addition of a small amount of Si element can inhibit and optimize the diffusion process of Ni and Al, thus reducing the required coating thickness and promoting the transformation of the single NiAl phase to the Al-rich-Ni-rich NiAl phase[19–20].

The MCrAlY metal coating prepared by EB-PVD method is also widely used as surface thermal protection method for aero-engine hot-section components[21]. During the operation of the guide vane in a high temperature environment, the dense oxide film, i.e. thermally grown oxide (TGO), will also form on the surface of the MCrAlY metal coating, which acts as a role of thermal insulation, typically α-Al_2O_3. As time goes on, the remaining Al content in the coating gradually decreases, and the stable formation of α-Al_2O_3 cannot be maintained, and then a large amount of spinel-like secondary oxides, such as Ni, Cr, and Co form, resulting in TGO spallation and coating failure[22–24].

It can be seen that both coatings existing in the APU guide vane have Al-Si coatings, and the most significant difference between the two coatings is the lack of MCrAlY metal coating on the suction side of the vane. This structural design is because under the normal working conditions of the APU guide vane, the suction side of the upper surface of the vane is not directly subjected to air scouring, and the convection heat transfer is weaker than that at other areas, so the temperature resistance requirement is lower than that of the vane's leading edge, trailing edge and pressure side. Hence, in the case of a single-layer aluminum coating, this structure can basically meet the thermal resistance requirements under the designed working condition of the APU guide vane, and save the manufacturing and processing cost. On the contrary, as the leading edge and pressure side act as the direct scouring side of the high temperature airflow, and the actual working condition of the trailing edge is severer due to the limitation of the internal vent space, it is necessary to add MCrAlY metal coating for further thermal insulation. At the same time, due to the existence of the aluminized coating, the MCrAlY metal coating on the surface at these three areas is not easy to interact with the substrate in high temperature environment, thus reducing the loss of Al element[25]. It can be seen that the leading edge, trailing edge and pressure side of APU turbine guide vanes are the focus of this study.

2.2 Effect of area variation on thickness of high temperature protective coating for APU turbine guide vanes

The remaining thickness of the vane's high temperature protective coating is an important reference to reflect the actual service environment and overall performance changes of the component. Therefore, it is necessary to measure and analyze the thickness of the APU high pressure turbine guide vanes. As shown in Fig. 3, a relatively complete discarded APU guide vane is selected to measure the thickness of the MCrAlY coating in different areas. The thickness of MCrAlY coating is measured by SEM from point 1 to 10, following the sequence of trailing edge – pressure side – leading edge. According to the results shown in Fig.4, it can be seen that the thickness of MCrAlY coating on APU guide vane increases first and then decreases from trailing edge to pressure side and then to leading edge. The coating thickness near the starting point 1 (trailing edge) is relatively low, about 20 μm, and then as the test point moves forward, the thickness gradually increases. The maximum value of the thickness is near point 8 (the transition area between the pressure side and the inner side of the leading edge), and the maximum value is about 70 μm. After that, the coating thickness decreases rapidly, and the minimum thickness is near point 10 (outside the leading

Fig.3 Inlayed vane specimen and its selected marking points

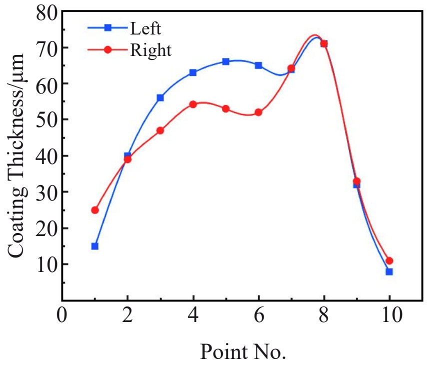

Fig.4 Variation curves of coating thickness on failed vanes

edge), about 10 μm. Through the comparative analysis of several APU high pressure turbine guide vanes with the same model, it is found that the variation trend of coating thickness is common.

Therefore, further research should be carried out on the basis of the microstructure morphology, element composition and actual working condition of the APU guide vanes to reveal different failure mechanisms in different areas. The specific research results and analysis will be elaborated in Section 2.3.

2.3 Micromorphology and failure mechanism of high temperature protective coating for APU turbine guide vanes

Areas of point 1 (trailing edge), point 7 (basin area), and point 10 (leading edge) were selected for the analysis of micromorphology and element composition. It should be noted that in order to better reflect the difference in microscopic morphology and failure mechanism of different vane areas, point 8 with the largest thickness was not selected, as it represents the transition zone between the pressure side and the leading edge. However, point 7, the pressure side area close to point 8, was selected for analysis and demonstration.

Fig. 5a shows the microstructure of the MCrAlY coating at point 1 (trailing edge). Combined with the EDS analysis result in Fig. 5b, it can be seen that the oxidation degree of the MCrAlY coating at the vane's trailing edge is more serious, and the oxygen atom content is about 31.85wt%. Meanwhile, the existence of Al-Si coating and Ni-Al interdiffusion zone can be observed in Fig. 5a, indicating that most of the oxidation of coating's trailing edge happens in the MCrAlY coating, and does not involve the internal structure. However, a large number of cracks, pores and oxidized areas can be clearly observed inside the MCrAlY coating, and the residual coating thickness in this area is relatively low (20 μm), which further proves that the degree of oxidation of the vane's trailing edge is more serious, resulting in coating burnout corrosion and spalling.

By comparison with other APU guide vane components that have failed in actual work, it can be found that the substrate has been exposed after the coating spallation due to the serious oxidation level of the trailing edge. In some certain

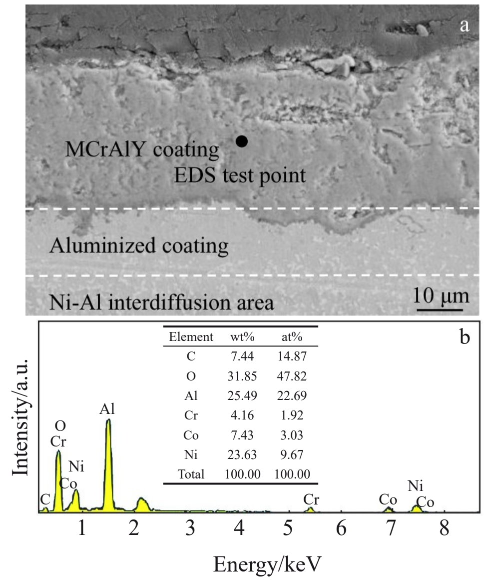

Fig.5 Micromorphology (a) and EDS analysis result (b) of MCrAlY coating on the trailing edge of the vane

areas, the substrate has even been ablated, resulting in material missing, as shown in Fig.6.

It should be noted that although the micro-cracks appearing here may be caused by thermal fatigue of the coating material, the phenomenon is mainly affected by high temperature ablation, because the thickness of the coating has been significantly reduced. In addition, as the MCrAlY layer and the Al-Si layer are both metal coatings, the difference in coefficient of thermal expansion (CTE) between them is very small; according to Slámečka et al's research[26], the calculated CTE of MCrAlY coating is around 15.0×10^{-6} K^{-1}, while the

Fig.6 Material missing from the trailing edge of APU guide vane due to ablation

CTE of Al-Si coating is in the range of 11.65×10^{-6}–18.42×10^{-6} K^{-1} in the variation range of the Si content from 53.72vol% to 23.29vol%[27], and such a structural system is not prone to thermal fatigue behavior.

The microstructure morphology of MCrAlY coating at point 7 (pressure side) is shown in Fig.7a. Combined with the EDS analysis results shown in Fig.7b, it can be seen that the oxidation degree of the MCrAlY coating at the vane's pressure side is relatively low, with almost no oxygen element, and only the constituent elements of MCrAlY materials such as Co, Cr, and Al can be found. Note that the C element detected in the energy spectrum analysis results is the interference of the inlaid resin material, while the Y element is not detected in Fig.7b because the content of the Y element in MCrAlY is low (only 0.5wt%), and conventional energy spectrometry instruments cannot accurately detect the presence of elements at this content level. Furthermore, the complete MCrAlY coating, Al-Si coating and Ni-Al interdiffusion zone can be observed in Fig. 7a. Compared with the above-mentioned vane's trailing edge area, no obvious cracks and pores are observed in the MCrAlY coating in the pressure side area, and the coating's morphology and density are at great level with the thickness of about 65 μm, which is close to the original MCrAlY coating thickness value, indicating no oxidative ablation, spallation or other damage.

According to the foregoing, it can be concluded that the failure modes of the trailing edge and the pressure side of the vane are both high-temperature oxidative damage, but the severity is different. By comparing the trailing edge and pressure side of the vane, it can be seen that there is a significant difference in the remaining thickness of the coating in these two areas. The coating in the trailing edge region is significantly much thinner while the coating oxidation degree in the pressure side is lower. This is because the airflow distribution inside the vane is different, the airflow path at and inside the pressure side near the leading edge is better, and the airflow can take away more heat, so the heat dissipation performance is the best and the degree of oxidation is the lowest. On the contrary, the internal vent space of the trailing edge is small and narrow, so the airflow is poor. Meanwhile, the internal processing technology at the trailing edge is difficult, and the high ambient temperature leads to severer oxidation of the trailing edge coating. In the previous research, Sadowski et al[28] have also proved this conclusion by simulation calculation, as shown in Fig.8.

Fig.9a and Fig.9b show the microstructure morphologies of MCrAlY coating at point 10 (leading edge). From these two figures, it can be obviously judged that the damage degree of MCrAlY coating at APU guide vane's leading edge is the most serious. Not only the MCrAlY coating in some certain areas is missing, but there are also oxidation regions of aluminized coating.

Meanwhile, combined with EDS analysis of oxidation corrosion products on the surface of MCrAlY coating in

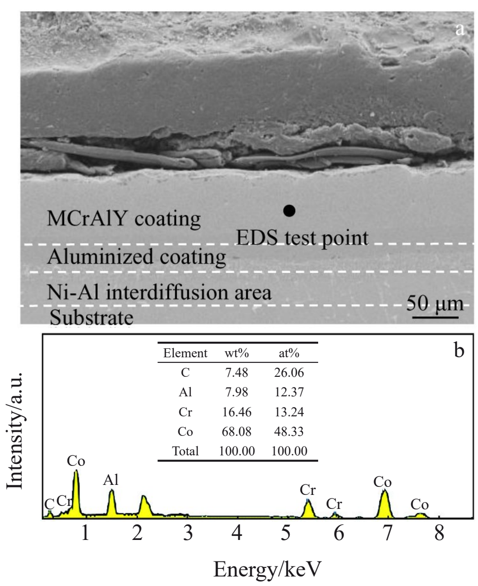

Fig.7 Micromorphology (a) and EDS analysis result (b) of MCrAlY coating in vane's basin area

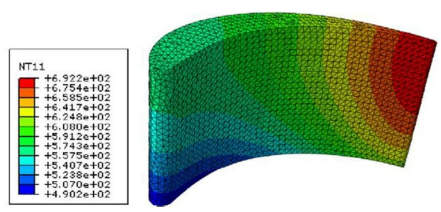

Fig.8 Temperature distribution of blade pressure surface when 1000 °C is applied for 200 s [28]

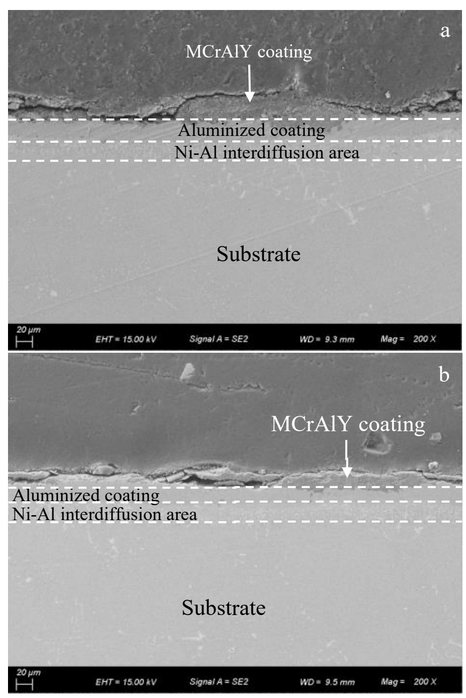

Fig.9 Micromorphologies of MCrAlY coating in different areas at point 10 of the leading edge of vane

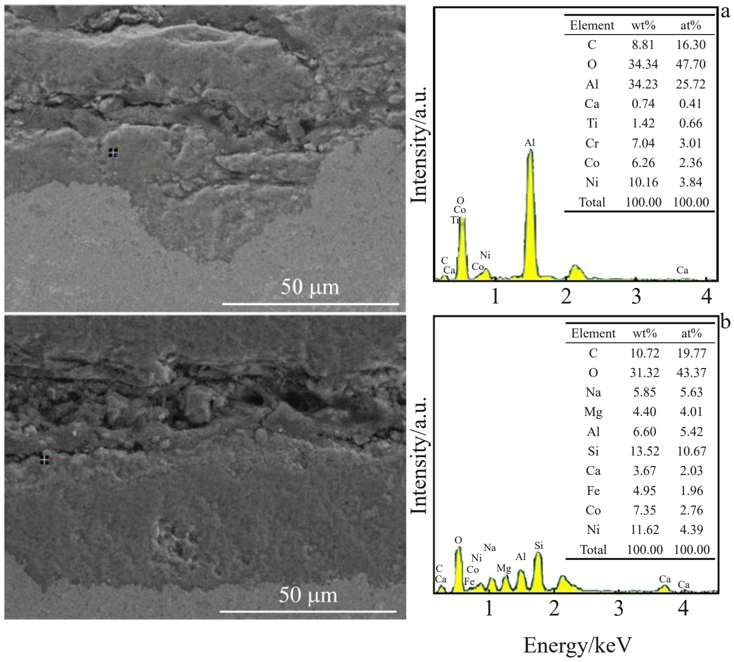

Fig.10 EDS analysis results of oxidation corrosion products on different surface areas of MCrAlY coating at the leading edge of the vane

Fig.10a and Fig.10b, it is found that the coating's failure mode in this area is not limited to high temperature oxidation corrosion. According to the two figures, there are certain contents of Ca, Mg, Si and other elements in the MCrAlY coating on the leading edge surface, which indicates that there is CMAS corrosion in the coating at the same time along with the oxidation corrosion. This result is exactly consistent with the actual working condition of APU turbine guide vanes. During APU operation, the leading edge is on the scouring surface of the high temperature airflow, and it can be eroded by dusts, sands, and ashes in the atmosphere and impurities in fuel, namely, CMAS corrosion.

The effect of CMAS on high temperature protective coatings depends on composition and the operating temperature of the hot-section components. Under lower temperature conditions (below 735 °C), CMAS particles impinge on the coating surface, which can lead to corrosion and wear damage, blockage of cooling holes, and partial spalling of the coating[29]. At higher temperature (above 1100 °C), CMAS first melts on the coating surface, then penetrates the coating and reacts with the Y element to cause the phase transition of the coating material[30–31]. In addition, during cooling, the coating corroded by CMAS becomes denser due to the filling of microcracks and pores, which reduces the strain tolerance of the coating, resulting in accelerated spallation failure of high temperature protective coating[32–33].

At the same time, as the vane's leading edge is directly scoured by the airflow, this position is the highest point of the flame temperature that the entire vane is subjected to during service[28] (as shown in Fig. 11), so there is also a certain degree of oxidation corrosion in this area itself. However, due to the better design and quality of ventilation holes in this area, the temperature of the

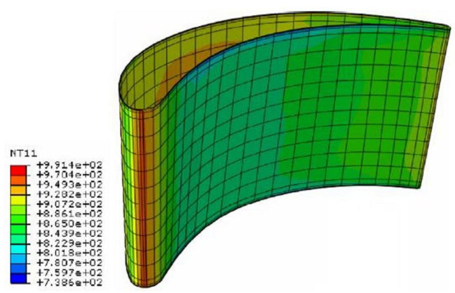

Fig.11 Temperature distribution of high temperature airflow in the vane area[28]

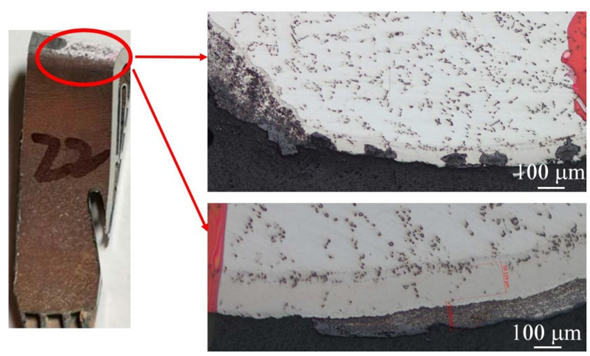

Fig.12 Coating thinning and spallation caused by CMAS corrosion-high temperature oxidation coupling effect

coating is lower than that of the trailing edge[28,34], so the effect of oxidation corrosion is not obvious. Taking the above factors into consideration, the phenomenon of the smallest coating thickness and the most serious coating damage in the leading edge area of the vane (Fig. 12) can be summarized as the coupling effect of predominant CMAS corrosion and high temperature oxidation corrosion as a supplement.

3 Conclusions

1) There are two different high temperature protective coating structures in aircraft APU guide vanes. The coatings at the vane's trailing edge, pressure side and leading edge are aluminized+MCrAlY structure, while the vane's suction side is a single Al-Si coating structure. This is because the upper surface of the vane, which is the suction side, is not directly scoured by the airflow, where the heat convection is weaker than other areas, so the thermal resistance requirement is lower than that of the vane's leading edge, pressure side and trailing edge. Therefore, in order to optimize the structure and save cost, only aluminized coating is prepared in this area. On the contrary, the actual working conditions of the vane's leading edge, pressure side and trailing edge are more severe, so it is necessary to add MCrAlY metal coating to enhance the thermal insulation property.

2) The coating thickness of failed APU guide vanes varies with the change of configuration areas. From the vanes trailing edge to pressure side and leading edge, the thickness of the MCrAlY coating increases first and then decreases. For the MCrAlY coating with the original thickness of 80 μm, the coating thickness from the very front of the pressure side to the trailing edge is reduced quasi-linearly from 70 μm to 20 μm. However, the lowest value of the coating thickness appears in the windward area of the vane's leading edge, with a thickness of only about 10 μm.

3) The coating thickness changes are caused by different failure modes in different areas. The SEM and EDS results show that due to airflow distribution difference inside the vane, the airflow path in the pressure side adjacent to the leading edge is better, and the airflow can take away more heat, so the heat dissipation performance is relatively good, hence the coating presents a high integrity with a low degree of oxidation. However, the small interior ventilation space at the trailing edge results in poor airflow, so air holes are more likely to be blocked. In this case, less heat is carried away by the airflow, thus resulting in a greater oxidative damage to the trailing edge coating.

4) The damage of the MCrAlY coating on the leading edge of the vane is the most serious. The MCrAlY coating in some area almost completely disappears, and the aluminized coating is also oxidized. Since the leading edge of the vane is located on the scouring surface, the scour surface encounters high temperature air flow during the operation of the APU, and is eroded by dusts, sands, volcanic ashes and other impurities in the fuel and/or atmosphere. Therefore, the failure mode of the coating in this area is mainly CMAS corrosion, while it also has a certain degree of high temperature oxidative damage due to the highest temperature of the airflow.

5) Through a comprehensive analysis of the scrapped components of the APU high-pressure turbine guide vane, the damage mode and failure mechanism of the different configuration areas of the vane are obtained. This helps to accumulate original data for the continuous airworthiness of aero-engine and APU key components, and fundamentally improves the reliability, availability, maintainability and safety of aircraft.

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飞机APU涡轮导向叶片高温防护涂层失效模式分析

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摘　要：利用扫描电镜（SEM）、能谱分析仪（EDS）等分析了国内某型在役APU涡轮导向叶片的结构特征与热防护机理，研究了叶片失效件中高温防护涂层的厚度变化与失效模式。结果表明：飞机APU导向叶片中存在渗铝涂层+MCrAlY涂层与单一渗铝涂层2种不同的涂层结构；APU导向叶片失效件的MCrAlY涂层厚度从叶片尾缘—叶盆—前缘区域呈先增大后减小的趋势；受叶片构型影响，叶片尾缘区域涂层的氧化程度较严重，而叶盆区域越靠近前缘的位置涂层氧化损伤程度越低，但叶片前缘区域由于受CMAS腐蚀与高温氧化的耦合作用使得该区域涂层损伤最为严重。

关键词：涡轮导向叶片；高温防护涂层；MCrAlY；高温氧化；CMAS腐蚀

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