Effect of La$_2$O$_3$ on resistance to high-temperature oxidation and corrosion of aluminized and aluminum-chrome coating

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Abstract
In this paper, the effect of La$_2$O$_3$ on resistance to high-temperature oxidation and corrosion of aluminized and aluminum-chrome coating on the nickel-based superalloy GH625 was investigated. The results show that the addition of La$_2$O$_3$ can dramatically reduce the oxidation weight gain of coating, promote the formation of a protective oxide film and improve the adhesion of oxide film, which can enhance high-temperature oxidation resistance of the coating. In addition, La$_2$O$_3$ can also obviously improve the high-temperature corrosion resistance of the coating. After 100 h of the high-temperature corrosion, the corrosion weight gain of Al + La$_2$O$_3$ coating and Al-Cr + La$_2$O$_3$ coating was 6.01 mg cm$^{-2}$ and 4.49 mg cm$^{-2}$, respectively, with a decrease of 50% and 33% compared with La$_2$O$_3$ free coatings. The addition of La$_2$O$_3$ can refine the grain size, reduce the alkaline dissolution of Al$_2$O$_3$, and inhibit the diffusion of corrosive elements, which can increase the high-temperature corrosion resistance of the coating.

1. Introduction
The nickel-base superalloy GH625 is one of the commonly used materials for the preparation of a turbine engine blade in a high-temperature environment and its composition is as shown in Table 1. This alloy can produce Cr$_2$O$_3$ protective film, which is easily decomposed and volatilized in a long-term high-temperature environment (1470 °C) [1]. Hence, its resistance to high-temperature oxidation and corrosion performance is not very good [2–4]. In order to improve the high-temperature performance of this alloy, some scholars studied the effect of high-temperature protective coating on the nickel-base superalloy. The results show that the Al coating can significantly improve the high-temperature corrosion resistance of the alloy. However, the high-temperature corrosion resistance of the alloy is a little poor [5]. This is because the Al$_2$O$_3$ formed on the surface of the Al coating can prevent the entry of oxygen atoms, but not that of corrosive ions.

Rare-earth element or rare earth oxide has the characteristics of low electronegativity, high activity, and strong reducibility, and is often used as a catalyst for the oxidation reaction. The addition of a small amount of rare earth or rare earth oxide in the coating can significantly increase the adhesion and the peeling resistance of the oxide film and improve the high-temperature performance of the coating [6–8]. Lanthanum (La) in La$_2$O$_3$ is the most active element among the 17 rare-earth elements (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y, Sc), but there are not many studies related to the effect of La$_2$O$_3$ on performance of the coatings. Its effect mechanism on high-temperature oxidation and corrosion is not also clear. Therefore, it is of great research significance and value to study the effect of La$_2$O$_3$ on the high-temperature oxidation and corrosion resistance of Al and Al-Cr coatings.

In this paper, the effect of La$_2$O$_3$ on the high-temperature oxidation and corrosion resistance of Al and Al-Cr coatings of GH625 alloy was investigated to improve its high-temperature performance. The effect mechanism
of La2O3 which mainly was used as a catalyst and to refine grain was also studied in order to provide reference for the optimization of high-temperature oxidation and corrosion resistance of Al and Al-Cr coatings.

2. Experimental

In this paper, the Al and the Al-Cr coatings were prepared by adding La2O3 to the surface of nickel-base superalloy GH625 by thermal diffusion (TD) neutral salt bath method. The size of the sample was 10 mm × 10 mm × 3 mm. All surfaces of the specimens were ground by 400# and 600# silicon-carbon papers in turn. Subsequently, a suitable amount of diamond polishing agent was sprayed on the polishing cloth, and the samples were polished on the polishing machine (Model: MP-2A) at 300 r min⁻¹. The osmotic agents consisted of NaCl, BaCl₂, NaF, Cr₂O₃ and Al. The detailed compositions of four different salt baths were as shown in table 2. The reagents were weighed by an electronic balance with an accuracy of 0.1 mg, and mixed together, stirred uniformly, placed in a crucible, and kept in an electric drying oven at 100 °C for 2 h in order to sufficiently eliminate residual moisture and prevent the samples from being oxidized and corroded when the coating was deposited. The osmotic agents were then mixed into a box-type resistance furnace and heated to 800 °C for 2 h before adjusting the temperature to 970 °C. Finally, the furnace temperature was adjusted to 950 °C, and the sample was put into the osmotic agents and kept for 4 hours. The Al and Al-Cr samples were treated with tempering heat treatment before oxidation and corrosion experiment, and the tempering process was 200 °C × 2 h. The purpose of heat treatment is to homogenize the microstructure of the coatings, reduce the residual stress of the substrate.

The high-temperature oxidation experiment in this paper was conducted according to the HB5258-2000 standard on the measurement method for the determination of oxidation resistance of steel and high-temperature alloys. The high-temperature corrosion experiment also used salt corrosion method, and the experimental test was investigated at 1000 °C for 100 h. The scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS) was used to observe the surface morphologies and identify the chemical composition of the samples, respectively. The oxidation kinetics curves, corrosion kinetics curves, phase composition, surface and cross-sectional morphologies of the samples were analyzed in order to study the high-temperature oxidation and corrosion mechanism, and to explore the effect of La2O3 on the high-temperature oxidation and corrosion resistance.

3. Results

3.1. XRD phase analysis and surface morphologies

The XRD patterns of four kinds of coatings are as shown in figure 1. The phase of the Al coating is mainly composed of β-NiAl (ICDD PDF 65-3199), Ni₃Al₂ (ICDD PDF 65-3454) phase and a small amount of AlNi₃ (ICDD PDF 65-0144) phase. The surface of the Al-Cr coating also mainly consists of β-NiAl and Ni₃Al₂ phases, while the α-Cr (ICDD PDF 65-0694) phase replaces AlNi₃ phases in the Al coating. In addition, a small amount of Cr₂C₃ (ICDD PDF 11-0550) phase was detected. The Al + La2O3 coating is mainly composed of β-NiAl and Ni₃Al₂ phases. The richness of Al in β-NiAl is very important for the performance of the coating because it can generate a dense oxide film in high-temperature conditions and can prevent corrosive elements from entering the matrix material in corrosive environment [10, 11]. The main constituent phase of the Al-Cr + La2O3 coating is also β-NiAl. In addition, it contains a small amount of Ni₃Al (ICDD PDF 65-0144) phase and aluminum-chromium compounds. The chromium in the Al-Cr + La2O3 coating is distributed mainly in the inner layer with a small

| Ni  | Cr  | Fe  | Nb  | Mo  | C   | Mn  | Si  | Al  | Ti  | S   | P   | Cu  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Bal | 20–30 | <5  | 3.15–4.15 | 8–10 | <0.1 | <0.5 | <0.5 | <0.4 | <0.4 | <0.015 | <0.07 |

Table 2. Chemical composition of four salt baths in coating treatment (wt%) [9].

|          | Al     | NaCl  | NaF  | BaCl₂ | Cr₂O₃ | La₂O₃ |
|----------|--------|-------|------|-------|-------|-------|
| Al coating | 6      | 26    | 8    | 60    | —     | —     |
| Al-Cr coating | 9.5    | 22    | 8    | 50.5  | 20    | —     |
| Al + La2O3 coating | 6      | 25.7  | 8    | 59.3  | —     | 1     |
| Al-Cr + La2O3 coating | 9.5    | 21.6  | 8    | 49.9  | 10    | 1     |
amount in the outer layer in the form of a solid solution. The main reason is that the diffusion rate of the Cr element is relatively slower \[12\]. Chromium is easy to form Cr\(_2\)O\(_3\) protective film in a high-temperature environment, so the Al-Cr + La\(_2\)O\(_3\) coating has better resistance to high temperature.

The surface morphologies of the Al + La\(_2\)O\(_3\) coating and Al-Cr + La\(_2\)O\(_3\) coating are as shown in figure 2. The surface of the Al coating is relatively dense, which is formed by a continuous mushroom-cloud like material. The surface of the coating is scattered with some spinel-like white-bright particles, and the main components of the white-light particles are Al, La and O. They can be La\(_2\)O\(_3\) and Al\(_2\)O\(_3\). The adsorption of La\(_2\)O\(_3\) can enhance the service performance of the infiltrated layer, at the same time, the shedding of La\(_2\)O\(_3\) in some areas form mushroom shape on the surface of the infiltrated layer. The surface morphology of the Al-Cr + La\(_2\)O\(_3\) coating is similar to that of the Al + La\(_2\)O\(_3\) coating. The difference is that the mushroom-cloud like material in the Al-Cr + La\(_2\)O\(_3\) coating does not have a clear boundary line, and thus, the penetrating layer is more continuous and dense. The composition of the white-light particles is also Al, La and O, and its formation process on the surface morphology is the same as that of the Al + La\(_2\)O\(_3\) coating. It, however, has more and finer particles. The

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Figure 1. XRD patterns of four kinds of coatings. (a) Al coating; (b) Al-Cr coating \[9\]; (c) Al + La\(_2\)O\(_3\) coating; (d) Al-Cr + La\(_2\)O\(_3\) coating.

Figure 2. Surface morphologies of two kinds of coatings. (a) Al + La\(_2\)O\(_3\) coating; (b) Al-Cr + La\(_2\)O\(_3\) coating.
Table 3. The contents of the main elements on the surface of the two coatings (wt%).

|                  | Al  | Ni  | Cr  | La |
|------------------|-----|-----|-----|-----|
| Al + La$_2$O$_3$ | 39.4| 56.09| 3.71| 0.8 |
| Al-Cr + La$_2$O$_3$ | 34.23| 57.53| 6.54| 1.7 |

3.2. Resistance to high-temperature oxidation

3.2.1. Oxidation kinetic curves

The oxidation kinetic curves of different coatings oxidized at 1000 °C for 100 h are shown in figure 3. The oxidation kinetic curves show the same change trend, but the overall oxidation weight gain of the Al-Cr coating is less than that of Al coating, which is due to the chromium element in the Al-Cr coating. Chromium element can inhibit the diffusion of external oxygen, which can slow down the oxidation rate [13]. In the initial stage of oxidation, the oxidation weight gain of all the coatings was very fast because at this stage no protective oxide film had formed on the surface. After 20 h of oxidation, all the curves show a significant turning point and the oxidation rate quickly slowed down. Then the oxidation weight gain of the coatings shows a slowly increasing trend, and this is because, after the initial oxidation, a continuous and dense oxide film formed on the surface, making it difficult to diffuse oxygen inward the material during the subsequent oxidation. According to figure 4, the oxide layer is mainly a mixture of Cr$_2$O$_3$ and Al$_2$O$_3$, and the change of turning point of the curve is similar to that of YSZ/YSZ-10% La$_2$O$_3$ studied by Hossein et al [14]. After the coatings were oxidized for 100 h, the oxidation weight gain of the Al + La$_2$O$_3$ coating and Al-Cr + La$_2$O$_3$ coating was 0.38 mg cm$^{-2}$ and 0.30 mg cm$^{-2}$ respectively, which was reduced by 30.6% and 26.7% compared with non-added La$_2$O$_3$ coatings, and reduced by 59.57% and 68.09% compared with the substrate, indicating that the Al-Cr + La$_2$O$_3$ coating has better resistance to high-temperature oxidation than Al + La$_2$O$_3$ coating.

Compared with the La$_2$O$_3$ free coatings and substrate, it can be found that the addition of La$_2$O$_3$ significantly reduces the oxidation weight gain of the two coatings after oxidation for 100 h. Therefore, it can be seen that La$_2$O$_3$ can significantly improve the coatings resistance to high-temperature oxidation.

3.2.2. Characterization of coatings added with La$_2$O$_3$ oxidized at 1000 °C for 100 h

Figure 4 shows the XRD patterns of five samples oxidized at 1000 °C for 100 h. As shown in figure 4(a), the phase constituents of the substrate were Cr$_2$O$_3$ and a small amount of NiCr$_2$O$_4$. The surface of the Al coating was mainly composed of NiAl, α-Al$_2$O$_3$, NiAl$_2$O$_4$, and a large number of θ-Al$_2$O$_3$ phases. Compared to the Al
coating, the phase constituents of the Al-Cr coating were different, which were mainly composed of Cr2O3, NiAl α-Al2O3 and θ-Al2O3 phases. As shown in figure 4(b), the highest intensity of the diffraction peak in the phase diagram was NiAl phase, indicating that the content of NiAl in the two coatings was still sufficient, and it still had a strong resistance to high-temperature oxidation. However, at the same time, it also formed the Ni3Al phase during the oxidation process, which can result in the crack or shedding of the oxide film on the surface and weaken the coating’s resistance to high-temperature oxidation [15]. The oxide films in the two coatings are mainly composed of α-Al2O3 and θ-Al2O3, but the diffraction peak intensity of α-Al2O3 is stronger than that of θ-Al2O3, indicating that the transformation of θ-Al2O3 to α-Al2O3 was high. It is noteworthy that the content of θ-Al2O3 in the Al-Cr + La2O3 coating is much less than that of the Al + La2O3 coating, which illustrates that the transformation speed of θ-Al2O3 to α-Al2O3 in Al-Cr + La2O3 coating is faster than in the later.

Figure 5 shows the surface morphologies of different coatings oxidized at 1000 °C for 100 h. As can be seen from figure 5, there are many needle-like θ-Al2O3 on the surface of La2O3 free coatings, and the surface is very loose. With the addition of La2O3, the surface of the Al coating is distributed with a lot of irregular-shaped particles and mainly α-Al2O3. The surface of the Al-Cr + La2O3 coating is very smooth and composed of a
cluster of fine and uniform particles. According to the XRD analysis, the fine particles are mainly $\alpha$-$\text{Al}_2\text{O}_3$ and with a small amount of $\theta$-$\text{Al}_2\text{O}_3$ and NiCr$_2$O$_4$. In addition, some tiny holes appeared on the surface of the Al-Cr coating and this phenomenon may be due to the formation of Cr$_2$O$_3$ inside the infiltration layer during the oxidation process.

It can be seen that the $\alpha$-$\text{Al}_2\text{O}_3$ particles of the coatings added with La$_2$O$_3$ are finer, and the surface is more uniform and dense compared to La$_2$O$_3$ free coatings, which can prevent the oxygen diffusing into the material and improve the high-temperature oxidation resistance of these coatings.

The cross-sectional morphologies of five samples oxidized at 1000 °C for 100 h are as shown in figure 6, with the phases of the oxide film identified by EDS. It can be seen from figure 6(a) that the surface of the substrate was severely oxidized. Compared with the substrate, the Al coating was less oxidized, and most of the surface is covered by Al$_2$O$_3$, as in figure 6(b), and the diffusion zone is mainly composed of some milky-white substances. As can be seen from figure 6(c), the Al-Cr coating has a distinct cross-sectional structure and the surface of the outermost layer is covered by a continuous dense Ni-rich oxide scale and dark Cr-rich alumina oxide. It can be seen that the surface oxide film of the Al + La$_2$O$_3$ and Al-Cr + La$_2$O$_3$ coatings both appeared irregular in structure, and this is because, after 100 h of high-temperature oxidation, part of the oxide film in the surface layer fell off. The composition of the surface oxide film is Al$_2$O$_3$, and the oxide film is very thick, indicating that both of the coatings with added La$_2$O$_3$ have good resistance to high-temperature oxidation when compared with the substrate, the Al and Al-Cr coatings. In addition, the Cr-rich layer in Al-Cr + La$_2$O$_3$ coating with La$_2$O$_3$ is very dense and uniform, which can improve the resistance of the coating to high-temperature oxidation.
3.3. Resistance to high-temperature corrosion

3.3.1. Corrosion kinetics curves

Compared with the coating, the high-temperature corrosion resistance of the substrate is worse. When the experiment was carried out for about 50 h, a large area of the substrate surface was peeled off. Therefore, the experimental results of four samples which were corroded at 1000 °C for 100 h were analyzed. The corrosion kinetics curves of different coatings corroded in mixed salt of 75 wt% Na2SO4 + 25 wt% NaCl at 1000 °C for 100 h are as shown in figure 7. It can be seen that all the coatings had rapid corrosion weight gain at the initial stage. However, the weight gain for coatings with La2O3 was much smaller than that for La2O3 free coatings, indicating that La2O3 can inhibit corrosion weight gain. After 20 h of high-temperature corrosion, the corrosion weight gain rate of coatings all decreased due to the formation of the surface oxide film, which can inhibit the progress of the corrosion. The subsequent corrosion weight gain of the coatings shows a stable trend, and the corrosion weight gain of Al-Cr coating was less than that of Al coating. In particular, the weight gain of Al-Cr + La2O3 coating has been lower than that of other samples for a long time, and the oxidation weight gain has remained basically unchanged after corrosion for 80 h. This phenomenon can be attributed to the high content of chromium in the Al-Cr + La2O3 coating, which has better resistance to high-temperature corrosion and can inhibit corrosion weight gain [16]. When corrosion was carried out for 100 h, the corrosion weight gain of Al coating and Al-Cr + La2O3 coating was 6.01 mg cm−2 and 4.49 mg cm−2, respectively; a reduction of 50% and 33% compared with La2O3 free coatings. It can be seen that La2O3 can significantly reduce the corrosion weight gain and improve the high-temperature corrosion resistance of the coating.

3.3.2. Characterization of coatings added with La2O3 corroded at 1000 °C for 100 h

Figure 8 shows the XRD patterns of the four samples corroded in mixed salt of 75 wt% Na2SO4 + 25 wt% NaCl at 1000 °C for 100 h. The XRD patterns of samples in figure 8 (a) show that the surface of the Al coating is mainly composed of β-NiAl, NiAl2O4, NiO, Ni3Al and a small amount of Al2O3 along with Cr2O3 phase. While the main phases of the Al-Cr coating are β-NiAl, NiAl2O4, NiO, Ni3Al and a large number of Cr2O3. As can be seen from figure 8 (b), the main composition of Al + La2O3 coating was mainly α-Al2O3, which indicates that the transformation from θ-Al2O3 to α-Al2O3 had almost completed. In addition, the aluminum element consumption in the infiltrated layer was greater and the β-NiAl phase in the infiltrated layer was also significantly reduced. With the detachment of the oxide film, the inner oxide layer continues to oxidize to form θ-Al2O3, hence a small amount of θ-Al2O3 was detected by XRD. The main components of Al-Cr + La2O3 coating were α-Al2O3 and β-NiAl phases, indicating that the Al-Cr + La2O3 coating had no obvious degradation, and still had better resistance to high-temperature corrosion.

Figure 9 shows the surface morphologies of different coatings corroded in mixed salt of 75 wt% Na2SO4 + 25 wt% NaCl at 1000 °C for 100 h. It can be clearly seen from figure 9 that the surface of the Al coating with non-added La2O3 has a uniform network structure and contains many holes. The presence of the holes allows the corrosive material to easily enter the material, thereby accelerating the material’s corrosion failure. The surface of the Al + La2O3 coating consists of a large number of granular particles and traces of thin strips. From the XRD analysis, it is found that the particles are α-Al2O3 and the thin strips are θ-Al2O3. The surface of Al-Cr coating is denser, with the grain size smaller than that of Al coating. In addition, no cracks...
appeared on the surface of the coating, and the oxide film had not been exfoliated. Combined with the corrosion kinetics curves, it can be seen that the Al-Cr coating has better high-temperature corrosion resistance than Al coating. By comparison, it can be found that the structure of the coatings added with La2O3 is denser and the grain size is smaller than that of non-added coatings. That is why the addition of La2O3 can improve the coating’s high-temperature corrosion resistance.

The cross-sectional morphologies of the four samples corroded at 1000 °C for 100 h are as shown in figure 10. It can be seen from figure 10(a) that the Al coating is still covered by a layer of Al2O3, but the outermost layer is almost exhausted, and severe peeling results in many pits. As shown in figure 10 (b), the outermost layer of Al-Cr coating contains a large amount of dark NiAl and Cr precipitate phases still retains a certain thickness. It can be seen that the diffusion layer in the Al + La2O3 coating is very loose. This phenomenon illustrates that the element diffusion during the corrosion process is very severe, resulting in the consumption of the osmosis layer and weakening the high-temperature corrosion resistance of the coating. Although the thickness of the Al-Cr + La2O3 coating is smaller than that of Al-Cr coating without added La2O3, the surface of the coating is very smooth and dense, which can prevent corrosive elements from entering the interior of the material and
inhibit the progress of corrosion. In general, the resistance to high-temperature corrosion of Al-Cr + La$_2$O$_3$ coating is better than that of the other coating.

4. Analysis and discussion

The addition of La$_2$O$_3$ in the Al coating and Al-Cr coating can significantly improve the resistance of the coating to high-temperature oxidation and corrosion. The proper amount of La$_2$O$_3$ can improve the high-temperature properties of the coating due to its lower electronegativity and strong chemical affinity. The rare earth oxide La$_2$O$_3$ can accelerate the decomposition of the osmotic agent in the salt bath, and increase the potential energy of aluminum and chromium, so that more active aluminum atom and chromium atom are adsorbed on the surface of the sample, and continuously penetrate the interior of the matrix to form dense coating\cite{17,18}. In addition, the large radius of lanthanum atom can easily cause lattice distortion on the surface of the substrate, thereby promoting the diffusing of the aluminum atom and chromium atom into the matrix, and to form a dense protective oxide film. Compared with the La$_2$O$_3$ free coatings, the surface layer of the coatings added with La$_2$O$_3$ is denser, and the distribution of cross-sectional elements is more uniform. In general, the addition of La$_2$O$_3$ can refine the structure of the coating and improve high-temperature performance.

Under high-temperature oxidation and corrosion conditions, the surface of the coating added with La$_2$O$_3$ mainly is composed of Al-rich $\beta$-NiAl. The oxidation process was the formation of metastable $\theta$-Al$_2$O$_3$ in the early stage, and then the unstable $\theta$-Al$_2$O$_3$ gradually transformed into stable $\alpha$-Al$_2$O$_3$ with the extension of the oxidation. At the beginning of oxidation, Al$_2$O$_3$ and a small amount of Cr$_2$O$_3$ were formed on the surface of the coating and the oxygen activity between the infiltrated layer and the oxide film became lower. The failure of the coating at the end of oxidation is mainly due to the gradual depletion of the aluminum element in the penetrating layer, which can result in the crack and exfoliation of the protective oxide film. The addition of La$_2$O$_3$ can promote the formation of a stable and dense $\alpha$-Al$_2$O$_3$ oxide film, thus reducing the cracking and exfoliation rate of the coating and improving to high-temperature oxidation resistance of the coating\cite{19}.

The effect of La$_2$O$_3$ on resistance to high-temperature corrosion is similar to that of high-temperature oxidation. The addition of La$_2$O$_3$ can reduce the alkaline dissolution of Al$_2$O$_3$, promote the formation of a highly stable Cr-containing phase, improve the denseness of coating, prevent the corrosive elements spreading into the material and reduce the formation of holes in the coating, thus increasing the high-temperature corrosion resistance. In addition, Al-Cr coating has better resistance to high-temperature corrosion than Al coating and
the main reason for this phenomenon is that La$_2$O$_3$ can enhance the diffusion of chromium element in Al-Cr coating and slow down the corrosion rate coating.

5. Conclusions

This paper mainly studied the effect of La$_2$O$_3$ on the resistance to high-temperature oxidation and corrosion of Al coating and Al-Cr coating of GH625 alloy. The results show that:

1. The Al + La$_2$O$_3$ coating added with La$_2$O$_3$ is mainly composed of $\beta$-NiAl and Ni$_2$Al$_3$ phases, and the main phase of Al-Cr coating is $\beta$-NiAl phase. The $\beta$-NiAl phase is very important for the high-temperature performance of the coating, which can generate dense oxide film to protect matrix under high-temperature conditions and prevent corrosive elements from infiltrating into the matrix material in a corrosive environment. Therefore, the addition of La$_2$O$_3$ can improve the high-temperature performance of the coating.

2. After 100 h of high-temperature oxidation, the oxidation weight gain of Al + La$_2$O$_3$ coating and Al-Cr + La$_2$O$_3$ coating was 0.38 mg cm$^{-2}$ and 0.30 mg cm$^{-2}$ respectively, and the oxidation weight gain was reduced by 30.6% and 26.7% compared with that of La$_2$O$_3$ free coatings. La$_2$O$_3$ can promote the transformation of the $\theta$-Al$_2$O$_3$ to stable $\alpha$-Al$_2$O$_3$ on the osmotic layer, reduce the diffusion rate of aluminum element during the oxidization process, and has a certain refinement effect on the grain size. It can promote the formation of a protective oxide film and improve the adhesion of film and anti-stripping properties, thus improving high-temperature the oxidation resistance of the coating.

3. After 100 h of high-temperature corrosion, the corrosion weight gain of Al + La$_2$O$_3$ coating and Al-Cr + La$_2$O$_3$ coating was 6.01 mg cm$^{-2}$ and 4.49 mg cm$^{-2}$, respectively, and the corrosion weight gain was reduced by 50% and 33% compared with that of La$_2$O$_3$ free coatings. The addition of La$_2$O$_3$ can promote the formation of a continuous and dense protective oxide film, reduce the alkaline dissolution of Al$_2$O$_3$, inhibit the diffusion of corrosive elements, thereby improving the high-temperature corrosion resistance of the coating.

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References

[1] Peres V et al 2012 High temperature chromium volatilization from Cr$_2$O$_3$ powder and Cr$_2$O$_3$-doped UO$_2$ pellets in reducing atmospheres J. Nucl. Mater. 423 93–101
[2] Gu Y L et al 2016 Microstructural evolution and mechanical properties of TIG welded superalloy GH625 Transactions of Nonferrous Metals Society of China. 26 100–6
[3] Peng J W et al 2019 Preparation a nickel-aluminide bonded diamond tool by self-propagating high-temperature synthesis and strengthening by nickel-chromium-phosphorus alloy and copper Int. J. Refract. Met. Hard Mater 82 100–9
[4] Kwong J et al 2009 Minor cutting edge–workpiece interactions in drilling of an advanced nickel-based superalloy International Journal of Machine Tools & Manufacture. 49 643–58
[5] Chen M et al 2012 Oxidation and thermal shock behavior of a glass-alumina composite coating on K38G superalloy at 1000 °C Journal of Materials Science & Technology. 28 433–8
[6] Li D et al 2019 Prospect and status of iron-based rare-earth-free permanent magnetic materials J. Magn. Magn. Mater. 469 535–44
[7] Chen L et al 2016 Effect of rare earth alloying on creep rupture of economical 21Cr-11Ni heat-resistant austenitic steel at 650 °C J. Rare Earths 34 447–52
[8] Zhang M, Wang X H, LQu K and Liu S S 2019 Effect of rare earth oxide on microstructure and high temperature oxidation properties of laser cladding coatings on 3CrNiMo die steel substrate Optics & Laser Technology. 119 105597
[9] Li C, Xu X J, Wang S F, Cai C B, Ju S H, Huang J D and Yang S 2019 Microstructure and Properties of Al and Al-Cr coatings on nickel-based superalloy GH625 by a Thermal Diffusion Process Mater. Res. Express 6 046426
[10] Peng X, Li T and Pan W P 2001 Oxidation of a La2O3-modified aluminide coating. Scr. Mater. 44 1033–8
[11] Wang J, Zhang P X, Hu R, Li J S and Ma J 2015 Isothermal oxidation behaviors of packed aluminide coatings of Ni-Cr-W superalloy at 1100 °C Rare Met. Mater. Eng. 44 1169–72
[12] Chen B J, Zhou M, Jiang T and Li L 2019 Observation of diffusion behavior between Cr2O3, and calcium ferrite based on diffusion couple method at 1373 K J. Alloys Compd. 802 103–11
[13] Wang J P et al 2018 Hydrogen permeation properties of Cr2C3@Cr2O3/A12O3 composite coating derived from selective oxidation of a Cr-C alloy and atomic layer deposition Int. J. Hydrogen Energy. 43 21133–41
[14] Hossein K M, Majid M and Mojtaba G 2018 Hot corrosion performance and electrochemical study of CoNiCrAlY/YSZ/YSZ-La2O3 multilayer thermal barrier coatings in the presence of molten salt. Mater. Chem. Phys. 220 23–34
[15] Lee J H, Tsai P C and Lee J W 2009 Cyclic oxidation behavior and microstructure evolution of aluminized, Pt-aluminized high velocity oxygen fuel sprayed CoNiCrAlY coatings Thin Solid Films 517 5253–8
[16] Wang B et al 2007 Effect of nitrogen on electrochemical behavior of weathering steel in corrosion solution simulated industrial atmosphere Journal of Iron & Steel Research International. 14 350–4
[17] Lahmer M A 2018 The effect of doping with rare earth elements (Sc, Y, and La) on the stability, structural, electronic and photocatalytic properties of the O-terminated ZnO surface; a first-principles study Appl. Surf. Sci. 457 315–22
[18] Sharma S P, Dwivedi D K and Jain P K 2009 Effect of La2O3 addition on the microstructure, hardness and abrasive wear behavior of flame sprayed Ni-based coatings Wear 267 853–9
[19] Ning Z et al 2017 Microstructure and wear resistance of laser cladded Ni-based coatings with nanometer La2O3 addition Rare Met. Mater. Eng. 46 2092–6