Microstructure Investigation and Cyclic Oxidation Resistance of Ce-Si-Modified Aluminide Coating Deposited by Pack Cementation on Inconel 738LC

Parviz Nourpoor 1, Soheila Javadian 1,*, Alireza Sabour Rouh Aghdam 2 and Farzin Ghadami 2

1 Department of Physical Chemistry, Faculty of Science, Tarbiat Modares University, Tehran P.O. Box 14115-143, Iran
2 Department of Materials Engineering, Faculty of Engineering, Tarbiat Modares University, Tehran P.O. Box 14115-143, Iran
* Correspondence: javadian_s@modares.ac.ir; Fax: +98-21-82883455

Abstract: The synergistic effect of Si and Ce addition on the oxidation resistance of a pack cementation aluminide coating applied on a Ni-based IN738LC superalloy substrate was investigated in this study. The structural and thermal influences of both Si and Ce, focusing on morphology, oxidation behavior, and scale spallation tendency, are accordingly discussed based on the experimental results using X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray analyses (EDX). For this purpose, the oxidation resistance of the modified coatings was evaluated by measuring the weight gain of the coated samples after 16 h for each cycle at 1100 °C for a total of 50 cycles of the oxidation process. The investigations indicated that Si addition to the modified aluminide coating improves the oxidation resistance through the formation of β-NiAl and δ-Ni2Al3 phases, and also δ-Ni2Si phases. Furthermore, the addition of 1% Ce to the modified aluminide coating enhances the formation of the fine-grained microstructure of the β-NiAl and δ-Ni2Al3 and reduces the outward/inward diffusion of elements (so-called blocking effect), which significantly modifies the cyclic oxidation resistance. The oxidation enhancement also may be attributed to synergistic effects of Ce and Si addition during the deposition process that reduce the inward oxygen diffusion and reduce the growth rate of α-Al2O3 during oxidation tests.

Keywords: pack cementation; Ce-Si modified aluminide coating; cyclic oxidation resistance

1. Introduction

High-temperature oxidation and corrosion inevitably occur in the aggressive environment of gas turbine engines that are applied in aircraft, aerospace, navy, gas, and oil industries and power generation units. Nickel-based superalloys, due to their excellent mechanical strength and creep resistance at high temperatures, are widely used in the critical hot section of gas turbines such as combustion chambers, turbine stators, and rotors [1,2]. However, nickel-based superalloys are not able to provide significant resistance against high-temperature oxidation and hot corrosion during long-time exposure. Thus, the appropriate coating has to be applied to enhance the high-temperature oxidation and hot corrosion resistance of the nickel-based superalloys [3,4]. Thermal barrier coating (TBC), MCrAlY overlays, and diffusion aluminides coatings are promising candidates for the protection of the surface at high temperatures [5,6]. TBC coatings provide thermal insulation and thus lower the temperature of the metallic substrate by virtue of its thermal conductivity [7,8]. Thus, they are currently applied in the hot section parts at operational temperatures higher than 1100 °C, which need complicated and expensive technologies [5,9–11]. Versatile and cost-effective conventional aluminide diffusion coatings usually protect the hot section parts at lower temperatures, such as the low-pressure turbine (LPT) section at the 700–1100 °C temperature range in the gas turbines [12,13]. Currently, modified aluminide diffusion coatings are being investigated.
to improve the durability of hot section parts in gas turbines working at high temperatures [14–19]. The modified aluminide coatings improve the gas turbine performance by increasing the turbine inlet temperature (TIT) and prolong their time between overhauls (TBO) [20,21]. Conventional aluminide coatings have been modified by adding beneficial elements such as chromium [22], silicon [23], cobalt [24], and platinum [23,25], or by doping reactive elements (REs), e.g., hafnium, zirconium, cerium, lanthanum, yttrium, and other REs, by using numerous techniques such as pack cementation [26,27], chemical vapor deposition (CVD) [28–30], slurry, or co-diffusion methods [31–34]. Nonetheless, the addition of silicon into conventional aluminide coatings enhances the resistance against carburization, hot corrosion, and high-temperature oxidation [16,35,36]. On the other hand, the high silicon content has negative side effects on the mechanical performance of the coating, resulting in cracking and spallation. The problem of cracking and spallation in Si-modified aluminide coatings could be overcome using the optimum silicon reservoir phase [37,38] and REs contents doped in the coatings [39]. Cerium has a high affinity toward oxygen, a large atomic radius compared to nickel, aluminum, chrome, and cobalt, and low solid solubility in β-NiAl phases [15,40]. The optimized amount of cerium and cerium oxides deposited in the scale/coating interface and along grain boundaries leads to an improvement in the lifetime and thermal stability of the aluminide coatings. The optimized content of segregated cerium ions inhibits the rapid outward/inward intermetallic diffusion of elements along the coating grain boundary and causes a finer-grained microstructure of the β-NiAl and δ-Ni2Al3 phases in the coatings [41,42], which enhances the oxide scales adhesion, hot corrosion, and oxidation resistance of the aluminide coating [33,43–46]. Cerium mostly stays against the outward diffusion of aluminum ions and inward diffusion of oxygen through a process named “the blocking effect”. It is responsible for the reduction in the alumina scale growth rate on the surface of the coating [29,41,47]. Moreover, applying cerium or its oxides to heat-resisting alloys significantly increases the adherence of Al2O3 and Cr2O3 scales when silicon is present in the alloy [48]. On the contrary, the high content of cerium in the coating diffuses into the solid solution and increases the energy of the system by the distortion and mismatch of the β-NiAl lattice. Thus, a high cerium content diminishes resistance against hot corrosion and oxidation because of the rising rate of spallation and rumpling of the aluminide coatings [15].

In recent years, the addition of two beneficial elements to the conventional aluminide coating has been researched to overcome the above problems [15,49–51]. The synergistic Ce-Si addition effect on the high-temperature oxidation behavior of the modified aluminide coatings has not yet been investigated in detail. Thus, in the present work, the influence of Ce and Si and their synergistic influences on the high-temperature oxidation behavior of the aluminide coatings applied by the pack cementation process was investigated. In this regard, the different combinations of cerium and silicon amounts, focusing on their optimum synergistic effects, were comprehensively examined to find the optimized Ce-Si-modified aluminide coating. Then, the diffusion mechanism, properties, and synergism of contributing aluminum, silicon, and cerium elements were investigated through microstructural characterization as well as high-temperature oxidation properties. Finally, the optimum composition of the mentioned additive elements in the modified aluminide coating was determined.

2. Materials and Methods

2.1. Substrate Materials and Preparation

The cast Ni-base superalloy IN738LC was used as the substrate. The determined chemical composition of substrate superalloy using flame type atomic absorption spectroscopy (AAS) is listed in Table 1. The specimens were sliced into squares with dimensions of 20 mm × 20 mm × 2 mm by using wire-electrode cutting. The surface and the sides of all specimens were carefully ground with 800-grit SiC emery paper.
Table 1. Chemical composition of IN-738LC substrate used for applying aluminide coatings determined by AAS method.*

<table>
<thead>
<tr>
<th>Element</th>
<th>wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>Bal.</td>
</tr>
<tr>
<td>Cr</td>
<td>16</td>
</tr>
<tr>
<td>Co</td>
<td>8.5</td>
</tr>
<tr>
<td>Ti</td>
<td>3.4</td>
</tr>
<tr>
<td>W</td>
<td>2.6</td>
</tr>
<tr>
<td>Ta</td>
<td>1.7</td>
</tr>
<tr>
<td>Al</td>
<td>3.4</td>
</tr>
<tr>
<td>Mo</td>
<td>0.9</td>
</tr>
</tbody>
</table>

* Total content of pack mixture was measured as 60 g.

2.2. Coating Procedure

Regarding the deposition of the coatings using the pack cementation method, the substrate samples were degreased and cleaned in an ultrasonic bath containing acetone for 30 min and finally put into cementation pack boxes. Commercial pure powders of aluminum, silicon, CeCl$_3$, Al$_2$O$_3$, and NH$_4$Br (≥99.9% grade) with average particle sizes of all less than 270 mesh were then used as the main precursors of the pack cementation process. In this case, the ammonium bromide activator was used to promote the formation of halide gases of aluminum, silicon, and cerium to their diffusion into the substrate during the pack cementation process (see Figure 1). The specimens were buried in the uniform pack powder in a cylindrical steel retort following the procedure reported elsewhere [52]. The retorts were heated to 1000 °C at a flow rate of 6 °C·min$^{-1}$ and kept for 2 h. In order to investigate the effect of cerium on the properties of coatings, three different contents of cerium were used, which are listed in Table 2. Based on the oxidation resistance of coatings, optimized cerium content (1%CeCl$_3$ ≡ %0.76Ce) was selected. Then, according to Table 2, three different contents of silicon were changed in order to trace its effect on the properties of coatings.

Figure 1. Schematic representing pack cementation process.
Table 2. Composition of pack mixture for applying aluminide coatings *

<table>
<thead>
<tr>
<th>Sample</th>
<th>Code</th>
<th>Content of Composition (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Al</td>
</tr>
<tr>
<td>No.1</td>
<td>Ce0Si3</td>
<td>6</td>
</tr>
<tr>
<td>No.2</td>
<td>Ce1Si3</td>
<td>6</td>
</tr>
<tr>
<td>No.3</td>
<td>Ce2Si3</td>
<td>6</td>
</tr>
<tr>
<td>No.2</td>
<td>Ce1Si3</td>
<td>6</td>
</tr>
<tr>
<td>No.4</td>
<td>Ce1Si0</td>
<td>6</td>
</tr>
<tr>
<td>No.5</td>
<td>Ce1Si6</td>
<td>6</td>
</tr>
</tbody>
</table>

* Total content of pack mixture was measured as 60 g.

2.3. Microstructural Characterization

Scanning electron microscopy (SEM, Philips-XL30) was used to analyze the microstructure by examining the cross-section and surface of the coatings. The elemental composition and microstructure of the coatings were determined using element mapping (MAP) by using an energy dispersive spectrometer (EDS). The surface phase composition of the coatings was then investigated by X-ray diffraction (XRD, Philips X’Pert MPD) using Cu Kα radiation (1.5418 Å) at 40 kV and 40 mA. A low scanning rate of 0.02°/s was used to obtain the desired precision.

2.4. Cyclic Oxidation Tests

The evaluation of the hot oxidation resistance of the coatings was carried out by using weight change measurements during cyclic heating in air. The samples were ultrasonically cleaned in acetone, rinsed and dried. The prepared samples were weighed with a balance of 0.1 mg precision and placed on an aluminide ceramic pan for oxidation tests. All samples were placed in a furnace and examined under oxidation at 1100 °C during 50 cycles, where each cycle equals 16 h (Figure 2), and weight variations were recorded. The weight change per unit surface area was determined after each oxidation cycle. Finally, the surface of the samples was investigated by using SEM and XRD to characterize the surface properties of the coating.

![Figure 2](image-url)  
*Figure 2. The hot cyclic oxidation test diagram that was carried out on coated samples.*

3. Results and Discussion

3.1. Microstructure of Al-Si-Ce Coatings

In order to investigate the diffusion mechanism of Al-Si-Ce pack cementation, the samples Ce0Si3, Ce1Si0, and Ce1Si6 were characterized by using the SEM-EDX method,
which is shown in Figure 3 and Table 3. According to Figure 3, the coatings reveal a thickness between 40–50 µm for all cases. In addition, the coating cross-section shows its regions, including two layers: the outer layer that is ~35–45 µm thick and the diffusion zone that is ~3–5 µm thick. The sensible differences between the thicknesses of the top layers of various types of the modified coatings are mainly associated with the thickness tolerance caused by the pack cementation process. The diffusion zone indicates that the formation of the coating is based on a high-temperature low-activity aluminizing (known as HTLA) coating type that is primarily attributed to the outward Ni, Cr, and Co diffusion. Thus, in comparison to inward Al, Si, and Ce diffusion, the outward diffusion for elements such as Ni, Cr, Co, etc., gradually increased during the HTLA pack cementation process.

![Figures](image1.png)

**Figure 3.** Cross-sectional image micrograph of the modified aluminized coatings consisting of two distinguished layers, (a) Ce0Si3, (b) Ce1Si0, (c) Ce1Si6, (d) Ce1Si3, and (e) Ce2Si3 coatings.

**Table 3.** Elemental percentage (wt.%) on the selected samples by EDX analysis.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Ce0Si3</th>
<th>Ce1Si3</th>
<th>Ce2Si3</th>
<th>Ce1Si0</th>
<th>Ce1Si6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>34.80</td>
<td>41.67</td>
<td>42.66</td>
<td>54.49</td>
<td>41.86</td>
</tr>
<tr>
<td>Cr</td>
<td>9.86</td>
<td>11.06</td>
<td>10.61</td>
<td>1.34</td>
<td>11.82</td>
</tr>
<tr>
<td>Co</td>
<td>4.00</td>
<td>5.53</td>
<td>6.2</td>
<td>5.28</td>
<td>4.87</td>
</tr>
<tr>
<td>Al</td>
<td>46.90</td>
<td>38.63</td>
<td>33.67</td>
<td>32.25</td>
<td>37.51</td>
</tr>
<tr>
<td>Si</td>
<td>1.37</td>
<td>0.38</td>
<td>0.25</td>
<td>0.01</td>
<td>1.03</td>
</tr>
<tr>
<td>Ce</td>
<td>0.01</td>
<td>0.70</td>
<td>0.93</td>
<td>0.75</td>
<td>0.66</td>
</tr>
</tbody>
</table>
According to Table 2, which shows the composition of the coatings, the low rate of the diffusion of cerium to the substrate according to its large radius in comparison with nickel and aluminum is shown.

The cerium’s large atomic radius causes a low diffusion rate to the substrate in the pack cementation process [15]. According to Figure 4, the increase in nickel concentration and decrease in Al and Si concentration are shown as a scale in coatings. It can be attributed to the HTLA effect, which reduces the aluminum and silicon diffusion inside the superalloy. In addition, mainly cerium is placed into the grain boundary of $\beta$-NiAl and $\delta$-Ni$_2$Al$_3$ phases since it has a greater radius compared to nickel and aluminum (the radii of cerium, nickel, and aluminum are 0.185, 0.135, and 0.125 nm, respectively) and its effect in increasing the energy of the system. Thus, cerium is first to be replaced in grain boundaries and the scale/alloy interface, where the atomic dispersion is irregular [15,33]. The deposition of cerium in the grain boundary causes a finer-grained microstructure of the $\beta$-NiAl and $\delta$-Ni$_2$Al$_3$ phases, resulting in changing the mechanism of aluminum oxide and nickel oxide formation. XRD analysis was applied to study the major phase of the outer surface layer of coatings.

![Elemental distribution mapping of Ni, Al, Si, Ce](image)

**Figure 4.** Elemental distribution mapping of Ni, Al, Si, Ce in (a) Ce0Si3, (b) Ce1Si0, (c) Ce1Si6, (d) Ce1Si3, and (e) Ce2Si3 coatings.

As can be seen from Figure 5, the major phases of all samples are $\beta$-NiAl and $\delta$-Ni$_2$Al$_3$. According to relative peak intensities, the $\delta$-Ni$_2$Al$_3$ phase is dominant in the sample without cerium (Ce0Si3) compared to Ce1Si0 and Ce1Si6. In other words, the $\beta$-NiAl ratio is increased as cerium increases by 1%. This indicates that a 1% addition of cerium slightly increases the outward diffusion of nickel into the outer zone compared
to the inward diffusion of Al, which results in the formation of the β-NiAl phase. In the sample without silicon (Ce1Si0), there are only β-NiAl and δ-Ni2Al3 phases, whereas δ-Ni2Si is formed as the silicon ratio is increased by 3%. This indicates that the silicon deposit was mostly present in the solid solution of β-NiAl and δ-Ni2Al3. In addition, as can be observed, the value of added Ce in the modified coating is too low to be detected and compared by X-ray diffraction. Additionally, it can be concluded that deposited silicon is present in the form of NiAl(1-x)Si x and Ni2Al3-nSi n [22,53]. It is worth noting that the intensity of the Ni2Si phase is increased from the Ce0Si3 to Ce1Si6 sample according to the following relation (Equations (1)–(3)). In other words, the addition of silicon by up to 6% increases the amount of Ni2Si formation, leading to a greater resistance of the coating against hot oxidation [36].

\[
\begin{align*}
\text{Al} + \text{Ni} & \rightarrow \beta\text{-NiAl} \quad (1) \\
3\text{Al} + 2\text{Ni} & \rightarrow \text{Ni}_2\text{Al}_3 \quad (2) \\
[\text{Si}] + 2\text{Ni} & \rightarrow \delta\text{Ni}_2\text{Si} \quad (3)
\end{align*}
\]

![Figure 5. X-ray diffraction pattern of samples coated by pack cementation method at 1000 °C.](image)

### 3.2. High-Temperature Oxidation

As seen in Figure 6a, the effect of the cerium content is examined on silicon-modified aluminide coating. The samples containing cerium undergo a fast weight increase earlier, which is attributed to the high tendency of cerium towards oxidation. In Ce2Si3, an abrupt increase in mass gain just after 48 h of oxidation is reported regarding the high ratio of cerium ions. The higher ratio of cerium in Ce2Si3 is related to the cerium diffusion into the β-NiAl and δ-Ni2Al3 phases, increasing the lattice energy of the system by lattice distortion and exfoliation of the coating [33]. As seen in Figure 6a, the lowest weight loss and highest
hot oxidation resistance are observed in the Ce1Si3 sample containing cerium 1% [9]. The weight increase in Ce1Si3 is higher compared to Ce0Si3 at the beginning of the oxidation test. Regarding the high oxidation tendency of cerium, it reacts with diffused oxygen that is diffused along the grain boundary.

Figure 6. Cyclic high-temperature oxidation of Ce-Si-modified aluminide coatings at 1100 °C for 800 h. (a) For samples Ce0Si3, Ce1Si3, and Ce2Si3, (b) for samples Ce1Si0, Ce1Si3, and Ce1Si6, and (c) and (d) show the beginning of the oxidation test in detail.

Then, cerium deposits as CeO2 nanoparticles in the near-surface zone, and hence a higher weight increase is observed during the first 160 h of high-temperature oxidation [45]. As oxidation continues, the precipitated CeO2 fine particles located in the grain/phase boundaries can play the role of a diffusion barrier and suppress the subsequent scale-up diffusion of nickel, aluminum, and silicon elements [40,54]. In addition, the Ce1Si3 and Ce1Si0 with a finer-grained microstructure change the mechanism of aluminum oxide and nickel oxide formation and improve the adhesion of the alumina scale on the coating [43–45,55]. The samples containing 1% cerium with 0, 3, and 6% silicon were considered to study the effect of silicon on the oxidation rate (Figure 6b). A weight increase was reported in samples that could be attributed to oxygen diffusion into the system and the inception of the oxidation layer. A significant weight loss was observed after 160 h, showing a low resistance of the Ce1Si0 coating compared to samples containing silicon. As silicon increased to 3%, the weight increase dropped and no notable weight loss was reported until 256 h,
indicating an improvement in hot oxidation resistance. As the silicon ratio increased to 6%,
the weight increase was slighter, and notable weight loss occurred after 560 h in the hot
oxidation test. This also shows that the Ce1Si6 coating showed a 3.5 times higher oxidation
resistance compared to the Ce1Si0 coating. Strictly speaking, alumina scale adhesion can be
greatly improved by adding a small amount of cerium into the coating [56] and, according
to Equation (4), the presence of silicon can prevent the oxygen inward diffusion with the
formation of a protective surface scale and retard oxidation, resulting in an improvement
in the resistance of the hot oxidation [36].

\[
\delta-Ni_2Si + O_2 \rightarrow 2NiO+[Si] \tag{4}
\]

3.3. Characterization of Oxide Scale

The phases formed after 50 cycles of oxidation in the oxide layer were characterized
through XRD analysis as shown in Figure 7. As can be seen, the uniform and continuous
oxide scales (α-Al₂O₃ phase) were observed in all cases of coated samples. In addition, for
the case of the Ce1Si6 and Ce1Si0 coatings containing 1% of cerium, the cerium oxide phase
was slightly observed in those diffraction patterns. Additionally, in Ce1Si6 and Ce0Si3
coatings, a considerable amount of the δ-Ni₂Si phase was converted into the Al₂SiO₅ phase.
It is noteworthy that the SiO₂ phase could not be observed, whereas the Al₂SiO₅ phase was
detected. In addition, the Si contents in the hot oxidation process accelerated the conversion
of γ/-Ni₃Al to β-NiAl.

![Figure 7. X-ray diffraction of coated samples after 50 cycles of oxidation tests at 1100 °C.](image-url)
To clarify the difference in the oxidation performance of coatings, surface morphologies of the coatings were investigated in Figure 8. As can be seen, Ce1Si6 (Figure 8b) shows a finer morphology and less porosity compared to the oxidized Ce1Si0 (Figure 8a) and Ce0Si3 (Figure 8c) coatings. For the case of the Ce1Si6 coating, it can be seen clearly that the grain size and volumetric fraction of NiO (bright contrast in Figure 8b) were further reduced. In addition, the $\alpha$-Al$_2$O$_3$ appears homogeneous and uniform, with less porosity in most other areas (dark areas in Figure 8b). This implies that the fine-grained microstructure of the $\beta$-NiAl and $\delta$-Ni$_2$Al$_3$, as well as cerium ions sediment in the grain boundary, results in the formation of dense and equiaxed structures $[51,53]$. In other words, according to other related investigations $[41,52]$, this fact indicates that a simultaneous effect of cerium and silicon results in the formation of finer and continuous alumina compared to the hot oxidation test. As a consequence, the overall growth rate of the NiO scale was also blocked effectively by the segregation of cerium to its grain boundaries $[53,55,56]$. Furthermore, a magnified image analysis of the Ni-, Al-, and Si-rich phases is shown in Figure 9 for better clarification. As can be observed, the phase with lighter contrast is known as the Ni-rich phase, and another darker phase mainly consists of phases enriched with Al and Si.

Figure 8. The surface SEM image after 50 cycles of oxidation tests at 1100 °C for (a) Ce1Si0, (b) Ce1Si6, (c) Ce0Si3, (d) Ce1Si3, and (e) Ce2Si3 coatings.
The cyclic oxidation tests showed that the samples containing 1% Ce and 6% Si possess the highest hot oxidation resistance. The addition of 2% Ce, owing to the distortion of the β-NiAl and δ-Ni2Al3 phases, strictly decreases the hot oxidation resistance, and the coating is exfoliated after 450 h at 1100 °C. Through this, metallic ions with a higher mobility (e.g., Ni- or Al-ion), depending on their ionic activity, can diffuse more easily toward the surface to form a thicker oxide scale during the cyclic test (Figure 10a). In contrast, for Ce-Si-modified aluminide coating containing both Si- and Ce-ions, even with a finer structure, because of the suitable distribution of the Si-ions into the grains and concentration of Ce-ions through grain boundaries (owing to the higher ionic radius for Ce-ions), the diffusion paths have been extensively decreased. Thus, the outward diffusion of metallic Ni- and Al-ions was sensitively limited during cyclic oxidation testing (Figure 10b). The α-Al2O3 oxidation layer morphology (according to the structural investigations mentioned earlier) showed that finer grains are formed in samples containing optimum ratios of Ce and Si, which indicates that these elements improve the coating adhesion and oxidation resistance simultaneously. Therefore, the growth rate of the oxide layer was decreased and so the cyclic oxidation resistance was accordingly enhanced for Ce-Si-modified aluminide coating due to the synergistic effect of Si- and Ce-ions in decreasing the diffusion of metallic ions to form oxide scale on the coating surface [43]. The magnified surface SEM image, (a) as well as elemental mapping for Ni (b), Al (c), and Si (d) for the Ce0Si3 coating sample after 50 cycles of oxidation test at 1100 °C.

Figure 9. The magnified surface SEM image, (a) as well as elemental mapping for Ni (b), Al (c), and Si (d) for the Ce0Si3 coating sample after 50 cycles of oxidation test at 1100 °C.

The magnification of the surface SEM images, (a) Ni-rich phase, (b) Ni-Kα, (c) Al-rich phase, and (d) Si-Kα for the Ce0Si3 coating sample after 50 cycles of oxidation test at 1100 °C.
the highest hot oxidation resistance, in which a 2 mg/cm² weight loss of Ce-Si-aluminide was reported after 800 h. This is attributed to the synergistic effect of Ce and Si during the deposition process, which reduces the oxygen diffusion and reduces the growth rate of α-Al₂O₃ during oxidation tests.

![Diagram](image)

Figure 10. Mechanism of the oxide scale formation for (a) aluminide coating containing Si and (b) alumina coating containing both Si and Ce after cyclic oxidation test at 1100 °C for 50 cycles.

4. Conclusions

The synergistic effect of silicon and cerium on the oxidation resistance of an aluminide pack cementation coating of a nickel-based superalloy was investigated. The microstructure evolution of the coatings was investigated before and after the cyclic oxidation test at 1100 °C. The conclusion can be drawn as follows:

1. The cerium addition by 1% enhances the oxidation resistance, whereas the oxidation resistance is limited by increasing the cerium ratio to exceed 2%. This occurs through increasing the ratio of NiAl to Ni₂Al₃, inhibiting the outward/inward diffusion of intermetallic elements and oxygen, which is called the blocking effect, in the hot oxidation process, and promoting a finer-grained microstructure of the NiAl and Ni₂Al₃ phases in the coating.
2. Increasing the cerium ratio to up to 2% strictly decreases the oxidation resistance, and a noticeable weight loss was observed after 450 h, which is mainly attributed to cerium placed into the solid solution increasing the energy of the system by the distortion and mismatch of the β-NiAl and Ni₂Al₃ lattice.
3. Deposited silicon is mainly present in the form of NiAl1-nSin and Ni₂Al₃-nSin and δ-Ni₃Si in the coatings. The reaction of δ-Ni₃Si with oxygen forms active silicon atoms,
and the silicon contents promote the transformation of γ′-Ni₃Al into β-NiAl and Al, which improves the hot oxidation resistance of the coatings.

4. The simultaneous addition of 1% cerium and 6% silicon, which is the Ce1Si6 sample, limits the oxygen diffusion and can synergistically promote the formation of the continuous Al₂O₃ layer, which can enhance the hot oxidation resistance of the coating.

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