Effect of Al and Cr alloying by arc cladding on the high-temperature oxidation resistance of MoSi$_2$ materials

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Keywords: MoSi$_2$, alloying, Al, Cr, high temperature oxidation resistance

Abstract
Different proportions of Al and Cr alloying MoSi$_2$ were prepared by arc cladding with different mass fractions of MoSi$_2$, Al, and Cr as raw materials. The work studied the effects about of Al and Cr on the phase, high-temperature oxidation morphology, products, and high-temperature oxidation property of MoSi$_2$. The results confirmed that the volume expansion coefficient of Al$_2$O$_3$ generated by material oxidation was low which could reduce the degree of mismatch and the cracks in the oxide film. Cr element had a poor effect on enhancing the continuity and compactness of the oxide film, however, it could improve the stability of t-MoSi$_2$ formation after arc cladding. MoO$_3$ was not formed in the MoSi$_2$ material added with Al and Cr show the surface oxidation. A dense and continuous Al$_2$O$_3$–SiO$_2$ oxide film was formed, and no cracks holes were found in the oxide film. After oxidation at 800 °C–1200 °C for 120 h, the sample still maintained good oxidation protection. According to the calculation of oxidation kinetics, the MoSi$_2$ material added with Al and Cr had good oxidation resistance. 3% Al + 9% Cr + 88% MoSi$_2$ had the optimal high-temperature oxidation resistance about four times than pure MoSi$_2$.

1. Introduction

In the past few decades, experts have developed new material systems, providing many material systems with better performance than nickel-base super–alloy for the aerospace industry with increased energy efficiency [1–8]. Perepezko J H et al [1, 2] have made great achievements in the study of Mo–Si alloys and compounds. They found that Mo–Si alloys and compounds can work at higher temperature than nickel–based alloys, and keep high-temperature properties. Zhai R X [4] et al found that the Mo substrate shows good high temperature oxidation resistance at 1300 °C after adding Mo–Si coating. Ouyang G Y et al [5] prepared Mo–Si composite coatings on Mo–W–Si–B alloy and studied their high temperature oxidation resistance. They found that the material shows good oxidation resistance and almost zero mass change.

MoSi$_2$ with a C11b structure is considered as one of the ideal high-temperature service materials in Mo–Si system because of its good electric conductivity, excellent thermal conductivity, and low thermal expansion. However, its engineering application is limited due to the limited mechanical properties at room temperatures and poor oxidation resistance at intermediate temperatures [9–16]. In high-temperature oxidation, MoSi$_2$ forms dense and continuous SiO$_2$ film on the surface, which prevents oxygen from diffusing into MoSi$_2$, and has good oxidation resistance [17–25]. Whereas, Mo prefers O to Si form MoO$_3$ at the medium temperature, hindering the protection of MoSi$_2$ by SiO$_2$ films and leading to ‘pesting’ phenomenon.

The ‘pesting’ of MoSi$_2$ have been studied in [26–30]. The results show that the oxidation rate of MoSi$_2$ changes with the increased temperature, and the ‘pesting’ just occurs in the air at about 500 °C S H Wen et al [31] found that MoSi$_2$ with micro-crack is broken after oxidation, but the single-crystal MoSi$_2$ without cracks is opposite. Westbrook et al [32] also suggested that the catastrophic oxidation of MoSi$_2$ is attributed to preferential diffusion between elements and grain boundary embrittlement. Many researchers have also pointed
out that oxidation occurs preferentially in cracks and holes. The internal stress generated by the oxide growth in these defects leads to the pulverizes the samples. Therefore, the service temperature and internal defects are the key factors affecting the pulverization of MoSi2.

Alloying is one of the main methods to improve the poor oxidation resistance of MoSi2 at medium temperatures. The properties of MoSi2 can be improved by adding alloying elements. L IngeMarsson et al [33] added Al element in MoSi2, and Mo (Si, Al)2 composite forms a continuous alumina protective layer at 1500 °C to improve the high-temperature oxidation of MoSi2. Hou et al [34] studied the high-temperature oxidation behaviors of MoSi2 materials with different Al contents. When oxidized at high temperatures, Al and Si form a mixed oxide film to protect MoSi2 materials. The content of Al is inversely proportional to the oxidation resistance. Jiang et al [35] studied the influence of Al and Cr elements on the oxidation property of MoSi2 materials at the atomic scale by density functional theory. The calculation results show that the Si–O bond is the main factor to prohibit diffusion. Al and Cr elements can improve the oxidation resistance of MoSi2. Dou Hu et al [36] prepared MoSi2/Cr coatings on C/C materials. Cr element changed the crack propagation path under the thermal cycle environment at 1500 °C, thus releasing the thermal stress in coatings and further extending the service life of coatings. Adding Al and Cr elements can significantly improve the service performance of MoSi2 materials.

In recent years, TIG arc cladding has become a high-efficiency, low-cost surface treatment technology, widely used in surface repair and modification of various metals [37]. However, the modification of refractory metal silicide coatings by TIG arc cladding is rarely reported. In this work, MoSi2 materials were prepared by TIG arc cladding. Different contents of Al and Cr elements were added to study the synergistic alloying of Al and Cr elements on the high-temperature oxidation resistance of MoSi2, expecting to improve the service performance of MoSi2-coating materials. It provides the interface structure and performance of the refractory-metal silicide coating.

2. Experimental procedure

2.1. Preparation of alloy powder and substrate

The mixed powders with the mass fraction of 100% MoSi2, 3% Al + 97% MoSi2, 3% Cr + 97% MoSi2, 9% Cr + 91% MoSi2, 3% Al + 3% Cr + 94% MoSi2, and 3% Al + 9% Cr + 88% MoSi2 were weighed, respectively. Besides, they were ball milled by QM-3SP4 planetary mill, with the ball milling speed of 200 r min⁻¹ and the ball milling time of 8 h.

Pure Mo alloy (Mo >99.99%) were selected as substrate and cut into 20 × 20 × 8 mm by a wire-cutting machine. The wire cutting traced on the substrate surface was removed by 240, 400, 600, 800 sandpapers. The substrates were cleaned in an ultrasonic cleaner for 1 h to remove surface stains.

2.2. Preparation of MoSi2 material

A powder layer was prepared on the substrate by presetting powders. The thickness of the powder layer was 5 mm, and alcohol was used as the adhesives. The preset powder was dried in the oven (DHG101-3A, 4.5 kW, ShangHai) at 120 °C for 10 min. TIG arc cladding (EASB 4300iw, Poland) was used cladding experiments on the preset powder.

The parameters of TIG arc cladding were as follows: a cladding current of 160 A, a cladding voltage of 220 V, a welding torch height of 5 mm, an argon content 8 l min⁻¹, and a welding torch scanning speed of 120 mm min⁻¹.

2.3. High-temperature oxidation test

The oxidation experiment was carried out in the KBF1400 box-type heat-treatment furnace. The oxidation samples were cut into 6 × 6 × 8 mm cubes by a wire-cutting machine. The wire cutting traced on the sample surface was removed by 240, 400, 600, 800, 1000, 1200, 1500, 2000 sandpapers. The polished samples were cleaned in an ultrasonic cleaner for 1 h, and the oil pollution left by wire cutting was removed and dried. The oxidizing temperature was 800, 1000, 1200 °C with an oxidizing time of 120 h. The samples were removed and weighed from the furnace every 12 h in the corundum crucible.

2.4. Morphology and phase analysis

Bruker D8 Advance x-ray diffractometer (Cu Ka radiation; θ = 0.03°) was used to detect the phase composition of the material, and Jade software was used to characterize phases in XRD. The morphology of the material was observed by Sigma500 field emission scanning electron microscopy (SEM, ZEISS, Germany). An energy dispersive spectrometer (EDS, Oxford) was used to analyze the element distribution in the material.
3. Results and discussion

3.1. Microstructure of Al and Cr alloying

Figure 1 shows the x-ray diffraction patterns of Al and Cr alloying MoSi2. MoSi2 was an intermetallic compound with a metastable C40 structure (h-MoSi2) above 1900 °C and a stable C11b (t-MoSi2) structure at room temperatures [38]. After arc cladding, there was macro residual stress in the sample causing the diffraction peak to shift slightly [39]. The unstable h-MoSi2 phase could not be completely transformed into the t-MoSi2 phase at high temperatures due to the high cooling rate of the sample. Therefore, there were a large number of h-MoSi2 phases in the material at room temperatures.

The Mo–Al and Cr–Si bonds were slightly enhanced compared with the Mo–Si bond [35], and the MoSi2 material added with Al consisted of Mo(Si, Al)2, h-MoSi2, t-MoSi2 and a small amount of Mo5Si3. The MoSi2 material with added Cr consisted of t-MoSi2, h-MoSi2, CrSi2 and a small amount of Mo5Si3. The diffraction peaks of t-MoSi2 after alloying with Al and Cr elements occupied a dominant position in the pattern.

Figures 2, 3 and table 1 show the changes in element distribution before and after oxidation at 1200 °C. After arc cladding, Mo(Al, Si)2 was formed by Al, Mo, and Si. Cr uniformly distributed in the material (see figure 2).

After oxidizing at 1200 °C (see figure 3), the content of Al decreased (see table 1). Al2O3–SiO2 mixed oxide film form at low temperature because of the low formation energy of Al. Cr element changes from the dispersion state to the segregation state. A part of Cr exists in the oxide film in the form of agglomeration (see figure 7), and the other part of Cr exists in the material in the form of segregation (see figure 3). It indicated that adding Al and Cr elements can improve the stability of forming the t-MoSi2 phase at room temperatures.

3.2. High-temperature oxidation products and micro-morphology

Figure 4 shows the surface x-ray diffraction patterns after oxidation at 800 1000 and 1200 °C for 120 h, respectively. Mo preferentially forms volatile substance MoO3 with O at 800 °C, which hinders the continuity of SiO2 on the oxidizing surface. According to thermodynamic analysis [34, 39], Al2O3 has low free energy and critical partial-pressure value; therefore, Al is preferentially oxidized to Si. The driving force of Al2O3 formation weakens with the increased Al2O3 phase, and Si gradually oxidizes to form SiO2 with the increased activation energy.

Figure 4 shows that the oxidation product of Cr belongs to the Cr2O3 phase with few diffraction peaks. Meanwhile, the t-MoSi2 and trace MoO3 phases are detected in the surface layer. Although Cr cannot form a stable and effective oxide layer in the oxidizing environment, it inhibits the formation of volatile substance MoO3 and improves the high-temperature stability of MoSi2.
Figure 5 shows the surface oxidized morphology of Al- and Cr-alloying MoSi₂ at 1200 °C. The oxide film surface forms reticulate cracks without adding alloying elements (see figure 5(a)). Figure 4 and table 2 show that oxide film mainly consisted of SiO₂ and MoO₃. The volume expansion caused by oxidized Mo is the main cause of mesh cracks. The oxide film formed by oxidized holes on the surface is relatively loose due to volatilized MoO₃.

Figures 5(c) and (d) show the oxidized surface with 3%Cr and 9%Cr, respectively. Figure 4 and table 1 show that the oxide film mainly consists of SiO₂, Cr₂O₃, and a few MoO₃. The number of cracks and oxidized holes in the oxide film is significantly reduced.

Figures 5(e) and (f) show the synergistic effect of Al and Cr. Figure 4 and table 2 present that the oxide film mainly consists of SiO₂, Al₂O₃, Cr₂O₃, and a few MoO₃.

In summary, the synergistic addition of Al and Cr improves the continuity and compactness of the oxide film.

3.3. High-temperature oxidation behaviors
Figure 6 shows the oxidized morphology of Al and Cr alloying MoSi₂ at 1200 °C. After oxidation for 120 h, cracks and holes appear in the oxide film formed by pure MoSi₂ (see figure 6(a)). The formation and volatilization of MoO₃ destroy the continuity of the oxide film, leading to cracks and holes in the oxide film eventually.
The low volume expansion coefficient of Al2O3 formed by adding Al element can reduce the degree of mismatch and cracks. Therefore, figure 6(b) shows the holes without crack defects.

After adding Cr, cracks and oxidized holes of the oxide film decrease (see figures 6(b) and (d)). In table 3, the Mo contents in areas 3 and 4 decrease significantly, and Cr inhibits the volatilization of MoO3 and improves the stability of MoSi2.

Table 3 and figures 7(b)–(e) show the domination of Al2O3–SiO2 oxide film by adding Al and Cr. Cr agglomerates in the oxide film (see figure 7(c)). The oxide film has no holes and cracks, indicating that the synergistic addition of Al and Cr is conducive to improving the compactness and continuity of the oxide film.
3.4. High-temperature oxidation kinetics

Figure 8 shows the mass change relationship of Al- and Cr-Alloying MoSi$_2$ at oxidizing temperatures. Mo preferentially reacts with O to form volatile MoO$_3$ at medium temperatures. Al$_2$O$_3$ has low free energy, so preferential Si is oxidized to form an oxide film to stop the loss of Mo. Therefore, the sample with Al shows increased oxidation, with an average oxidation increase of 4.42 mg cm$^{-2}$. The above results show that Cr element has a poor effect on improving the oxidation resistance of MoSi$_2$. Therefore, the samples with added Cr show oxidation loss. The average oxidation losses are 0.22 (100% MoSi$_2$), 1.33 (3% Cr + 97% MoSi$_2$) and 0.17 mg cm$^{-2}$ (9% Cr + 91% MoSi$_2$), respectively. After adding Al and Cr, the sample shows increased oxidation, with the average increase of 0.18 mg cm$^{-2}$ (3% Al + 3% Cr + 94% MoSi$_2$) and 0.06 mg cm$^{-2}$ (3% Al + 9% Cr + 88% MoSi$_2$). The synergistic addition of Al and Cr has high oxidized protection for MoSi$_2$ materials.

The driving force of oxidation increases gradually with the increased temperature. Al, Cr and Si prefer Mo and O to form an oxide film to isolate oxygen from the erosion of MoSi$_2$ materials. The synergistic addition of Al and Cr show oxidation loss. The average oxidation losses are 0.22 (100% MoSi$_2$), 1.33 (3% Cr + 97% MoSi$_2$) and 0.17 mg cm$^{-2}$ (9% Cr + 91% MoSi$_2$), respectively. After adding Al and Cr, the sample shows increased oxidation, with the average increase of 0.18 mg cm$^{-2}$ (3% Al + 3% Cr + 94% MoSi$_2$) and 0.06 mg cm$^{-2}$ (3% Al + 9% Cr + 88% MoSi$_2$). The synergistic addition of Al and Cr has high oxidized protection for MoSi$_2$ materials.

The driving force of oxidation increases gradually with the increased temperature. Al, Cr and Si prefer Mo and O to form an oxide film to isolate oxygen from the erosion of MoSi$_2$ materials. The synergistic addition of Al and Cr show increased oxidation. The average increases of oxidation at 1000 °C (see figure 8(b)) are 1.10 mg cm$^{-2}$ (3% Al + 3% Cr + 94% MoSi$_2$) and 0.56 mg cm$^{-2}$ (3% Al + 9% Cr + 88% MoSi$_2$), respectively. The average weight gains of oxidation at 1200 °C (see figure 8(c)) are 1.98 mg cm$^{-2}$ (3% Al + 3% Cr + 94% MoSi$_2$) and 1.47 mg cm$^{-2}$ (3% Al + 9% Cr + 88% MoSi$_2$), respectively.
Figure 5. Surface oxidation morphology of Al and Cr alloying MoSi2 at 1200 °C (a) 100%MoSi2; (b) 3%Al+97%MoSi2; (c) 3%Cr+97%MoSi2; (d) 9%Cr+91%MoSi2; (e) 3%Al+3%Cr+94%MoSi2; (f) 3%Al+9%Cr+88%MoSi2.

Table 2. Distribution of elements on the oxide-film surface of Al and Cr alloying MoSi2.

| Area | Element (at.%) |
|------|----------------|
|      | Mo  | Si  | Al  | Cr  | O   |
| 1    | 1.6 | 31.4| 0   | 0   | 67.0|
| 2    | 0.1 | 0.1 | 38.3| 0   | 61.5|
| 3    | 0.5 | 40.2| 0   | 8.1 | 51.2|
| 4    | 1.6 | 31.5| 0   | 0.6 | 66.3|
| 5    | 0.8 | 29.7| 0   | 3.0 | 66.4|
| 6    | 1.2 | 32.9| 0   | 1.4 | 64.5|
| 7    | 0.5 | 25.7| 4.7 | 3.0 | 66.1|
| 8    | 0.3 | 18.1| 3.8 | 13.3| 64.5|
| 9    | 0.1 | 25.1| 10.7| 0.1 | 64.1|
| 10   | 0.1 | 13.6| 23.4| 2.0 | 60.8|
The mass change of samples is approximately the same as parabolic law, expressed by:

\[ \Delta m^2 = k_p t + c \]  

(1)

where, \( \Delta m \) is mass change per unit area, mg; \( T \) the oxidation time, h; \( C \) the constant; \( k_p \), the parabolic rate

followed the Arrhenius equation, as shown in equation (2):

Table 3. Distribution of elements in the cross-section of the oxide film of Al- and Cr-alloying MoSi₂.

| Area | Mo   | Si   | Al  | Cr  | O   |
|------|------|------|-----|-----|-----|
| 1    | 9.8  | 23.1 | 0   | 0   | 67.1|
| 2    | 0    | 0.1  | 38.6| 0   | 61.3|
| 3    | 0.7  | 31.8 | 0   | 0.7 | 66.8|
| 4    | 0.1  | 30.2 | 0   | 9.8 | 59.9|
| 5    | 0    | 26.2 | 7.1 | 0.2 | 66.5|
| 6    | 0    | 21.2 | 11.0| 0.4 | 67.4|

Figure 6. Cross-section oxidized morphology of Al and Cr alloying MoSi₂, 1200 °C; (a) 100% MoSi₂; (b) 3% Al + 97% MoSi₂; (c) 3% Cr + 97% MoSi₂; (d) 9% Cr + 91% MoSi₂; (e) 3% Al + 3% Cr + 94% MoSi₂; (f) 3% Al + 9% Cr + 88% MoSi₂.
where, $k_0$ is the former factor; $R$ the common gas constant, 8.31 (J mol$^{-1}$); $T$ the oxidized temperature, $K$; $Q$ the activation energy of oxidation reaction (see table 4). Equation (3) is obtained by taking the logarithm on both sides of equation (2).

$$\ln k_p = \ln k_0 - \frac{Q}{RT}$$

Figure 9 shows the relationship between the oxidation rate and temperature of Al- and Cr-alloying MoSi$_2$. Table 4 shows the oxidized activation energy, which is the maximum after the synergistic addition of Al and Cr. It is lower when a single element is added.

Figures 4 and 5 show Cr can improve the stability of the MoSi$_2$, and the oxidation resistance of the MoSi$_2$ material is poor. Therefore, the activation energy of MoSi$_2$ materials with 3% and 9% Cr is lower than that of pure MoSi$_2$.

The oxygen affinity of Al is higher than Si, and the free energy of Al$_2$O$_3$ is lower than SiO$_2$ [33, 34]. Thus, the activation energy of the MoSi$_2$ material added with Al is also lower than that of pure MoSi$_2$.

Al$_2$O$_3$–SiO$_2$ oxide film forms on the surface after adding Al and Cr, which improves the high-temperature oxidation resistance of MoSi$_2$ materials. 3% Al + 9% Cr + 88% MoSi$_2$ has the best high-temperature oxidation
resistance, about four times that of pure MoSi₂. It confirms the conclusions of the above-oxidized interfaces and oxidation products.

4. Oxidation mechanism of Al- and Cr-alloying MoSi₂ materials

MoSi₂ was selectively oxidized to form the SiO₂ film. The film prevented oxygen from diffusing inward and played an effective protective role in MoSi₂ materials. However, the volatilization of MoO₃ formed holes and cracks in the SiO₂ film (see figure 10(a)). At high temperatures, cracks formed stable oxidation channels. Oxygen diffused to MoSi₂ material through cracks and formed volatile substance MoO₃ with Mo. The mass loss of MoSi₂ materials was fast, with its service ability decreased.

After adding Al and Cr (see figure 10(b)), Al and Cr were uniformly mixed with MoSi₂ and formed the Mo(Si, Al)₂-CrSi₂-MoSi₂ materials by arc cladding. Al and Cr reduced the forming temperature of the oxide film that formed at a lower temperature to reduce the oxidation volatilization of Mo. The oxide film after alloying by Al and Cr mainly consisted of Al₂O₃, Cr₂O₃, and SiO₂ by equations (4)–(8) because the free energy of Al and Cr was lower than Si [34, 36]. Cr₂O₃ existed in the oxide film through agglomeration, and its main function was to hinder the oxidation of MoSi₂ through cracks and to improve the stability of the oxide film. The Al₂O₃ wrapped cracks formed by preferential Si oxidation of Al to prevent oxygen from entering. Cracks generated by the oxide film were repaired through the flow of SiO₂ to form stable, dense mixed oxide film.

$$2\text{MoSi}_2 + 7\text{O}_2 \rightarrow 4\text{SiO}_2 + 2\text{MoO}_3$$  \hspace{1cm} (4)

$$2\text{Al} + \text{MoSi}_2 \rightarrow \text{Mo(Si, Al)}_2$$  \hspace{1cm} (5)

$$7\text{Cr} + 12\text{MoSi}_2 \rightarrow 2\text{MoSi}_2 + 7\text{CrSi}_2 + 2\text{Mo}_3\text{Si}_3$$  \hspace{1cm} (6)

$$4\text{CrSi}_2 + 11\text{O}_2 \rightarrow 2\text{Cr}_2\text{O}_3 + 8\text{SiO}_2$$  \hspace{1cm} (7)

$$2\text{Mo(Si, Al)}_2 + 3\text{O}_2 \rightarrow 2\text{MoSi}_2 + 2\text{Al}_2\text{O}_3$$  \hspace{1cm} (8)
Table 4. Oxidized activation energy of Al and Cr alloying MoSi$_2$.

| Component       | 100% MoSi$_2$ | 3%Al+97%MoSi$_2$ | 3%Cr+97%MoSi$_2$ | 9%Cr+91%MoSi$_2$ | 3%Al+3%Cr+94%MoSi$_2$ | 3%Al+9%Cr+88%MoSi$_2$ |
|-----------------|---------------|------------------|------------------|------------------|-----------------------|-----------------------|
| Q (kJ mol$^{-1}$) | 56.8          | 15.2             | 23.5             | 29.8             | 144.3                 | 206.6                 |
5. Conclusions

Al- and Cr-alloying MoSi$_2$ materials were prepared by arc cladding to study the effects on the high-temperature oxidation resistance of MoSi$_2$ materials. The main conclusions are as follows:

1. MoSi$_2$ prepared by arc cladding had a large amount of h-MoSi$_2$ at room temperature because of its high cooling rate. Al and Cr alloying could improve the stability of t-MoSi$_2$ phase formation at room temperature.

2. Al$_2$O$_3$ reduced the mismatching degree and the cracks of the oxide film because of its low volume expansion coefficient. Cr had the advantages such as inhibiting the formation of MoO$_3$, reducing the formation of holes, and improving the stability of the SiO$_2$ film. The synergistic addition of Al and Cr could promote the continuity and densification of the oxide film.

![Figure 9. Relationship between oxidation rate and temperature of Al and Cr alloying MoSi$_2$.](image)

![Figure 10. High-temperature oxidation mechanism of Al and Cr alloying MoSi$_2$.](image)
(3) A dense and continuous oxide film could be formed at 800 °C–1200 °C by adding Al and Cr. The increased oxidation increment obeyed parabolic law. From the oxidized activation energy, the oxidized effect of a single element alloyed on MoSi2 was poor. The synergistic addition of Al and Cr had a better oxidized effect and oxidation resistance. 3% Al + 9% Cr + 88% MoSi2 had the best high-temperature oxidation resistance, about four times that of pure MoSi2.

Acknowledgments

This study was financially supported by the Major Natural Science Research Projects of Universities in Jiangsu Province of China (Grant Nos. 17KJA430006, 18KJA430007). The Innovative Practice Program for Postgraduates of Jiangsu University of Technology (XJICX20_33).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Perepeko J H 2018 High temperature environmental resistant Mo–Si–B based coatings Int. J. Refrac. Met. H 71 246–54
[2] Perepeko J H, Bero J M, Sakidja R, T almy G and Zaykoski J I 2012 Oxidation resistant coatings for refractory metal cerments Surf. Coat. Technol. 206 3816–22
[3] Targhi V T, Omidvar H, Hadiavi S M and Sharifianfari F 2020 Microstructure and high-temperature oxidation resistance of hot dip silicized coating on Ni-base superalloy IN738L Mater. Res. Express 7 055627
[4] Zhai R X, Song P, Huang T H, Li G, Hua G, Huang W L, Li Q, Zheng B J and Lu S 2021 Microstructure and oxidation behavior of MoSi2 coating combined with diffusion barrier layer on Mo substrate at 1300 °C Ceram. Int. 47 10137–46
[5] Ouyang G Y, Ray P K, Thimmaiah S, Kramer M J, Akinc M, Ritt P and Perepeko J H 2019 Oxidation resistance of a Mo–W–Si–B alloy at 1000 °C–1300 °C: the effect of a multicomponent Mo–Si–B coating Appl. Surf. Sci. 470 289–95
[6] Yue G, Guo X P and Qiao Y Q 2021 Oxidation resistance and diffusion behavior of MoSi2/WSi2/(Nb, X)Si2 compound coating at 1400 °C C. Alloys Compos. 870 159498
[7] Zhu L, Ren X R, Wang X H, Kang X Q, Zheng R X and Feng P Z 2021 Microstructure and high-temperature oxidation resistance of MoSi2–ZrO2 composite coatings for Niobium substrate J. Eur. Ceram. Soc. 41 1197–210
[8] Gui J, Wang Z J, Hu S S, Lu W F and Shen J Q 2020 Microstructure evolution and mechanical properties of cold metal transfer additive manufactured Ti–6Al–4V wall with trace MoSi2 addition Mat. Sci. Eng. A 798 140160
[9] Liu W S, Ren X R, Chu H G, Zhang M L, Yang Q Q, Wang W G and Feng P Z 2021 Preparation of MoSi2–SiB coated with ZrO2 and oxidation inhibition coating on graphite by spark plasma sintering method Surf. Coat. Technol. 405 126511
[10] Wang J X, Yang K M, Wang J, Yang S Y and Zhang X L 2020 The enhanced structure stability and the reinforcement mechanism of 0.1Al2O3–ZrO2 reinforced MoSi2 composite coating Surf. Coat. Technol. 403 126358
[11] Ren X R et al. 2020 Influence of MoSi2 on oxidation protective ability of TaB2–SiC coating in oxygen-containing environments within a broad temperature range Journal of Adv. Ceram. 9 703–15
[12] Zhang G P, Sun J and Fu Q G 2020 Effect of mullite on the microstructure and oxidation behavior of thermal-sprayed MoSi2 coating at 1500 °C Ceram. Int. 46 10058–66
[13] Bi W, Sun S P, Bei S Y and Jiang Y 2020 Segregation of S at Mo(001)/MoSi2(001) interface Ceram. Int. 46 5030–7
[14] Wang J N, Luo R Y and Cui G Y 2019 MoSi2–modified C/SiC composites with enhanced mechanical performance and oxidation protection Corro. Sci. 160 108173
[15] Lu Q, Chen X and Fan J L 2019 Effect of Nb–Al–SiC elements combined with pre-oxidation treatment on the pesting resistance of MoSi2 Ceram. Int. 45 15807–14
[16] Nie X W and Lu Q 2021 Microstructure and high-temperature oxidation behavior of crack-free bentonite doped MoSi2 protective coating on molybdenum Corro. Sci. 184 109379
[17] Hu D, Fu Q G, Liu B, Zhou L and Sun J 2021 Multi-layered structural designs of MoSi2/mullite anti-oxidation coating for SiC-coated C/C composites Surf. Coat. Technol. 409 126901
[18] Zhu L, Wang X H, Ren X R, Kang X Q and Feng P Z 2021 Preparation and high-temperature oxidation resistance of multilayer MoSi2/MoSi2 coating by spent MoSi2-based materials J. Eur. Ceram. Soc. 194 3682–94
[19] Liang J, Liu X B, Ke J, Luo Y S and Liang L 2019 Preparation and high temperature oxidation resistance of laser deposited TiSi2/MoSi2/MoSi2, reinforced α-Ti/NI/SiTi composite coatings Surf. Coat. Technol. 372 56–64
[20] Cheng S, Geng J, Liu X C and Wang Y G 2020 Laser ablation behavior and mechanism of C/SiC coated with ZrB2–MoSi2–SiC/Mo prepared by HVOF Ceram. Int. 46 17752–62
[21] Wang L, Wang W Y and Fu Q G 2020 The improvement of the self-healing ability of MoSi2 coatings at 900 °C–1200 °C by introducing SiB6 J. Eur. Ceram. Soc. 40 2896–906
[24] Li S, Zhao D K, Wang H L, Zhang Y, Huang W J and Zhou Y 2020 Effect of Mg and Al alloying on the valence electron structure and properties of MoSi2-based alloys Mater. Chem. Phys. 249 123116
[25] Wang C C, Li K Z, He D Y and Shi X H 2020 Oxidation behavior of plasma-sprayed MoSi2-Yb2O3 composite coating at 1700 °C Ceram. Int. 46 9538–47
[26] Xiao L K et al 2020 Oxidation behaviour and microstructure of a dense MoSi2 ceramic coating on Ta substrate prepared using a novel two-step process J. Eur. Ceram. Soc. 40 3555–61
[27] Wu J Y et al 2020 Preparation and structure control of a scalelike MoSi2–borosilicate glass coating with improved contact damage and thermal shock resistance Ceram. Int. 46 7178–86
[28] Wang C C, Li K Z, He D Y and Shi X H 2020 Oxidation kinetics of supersonic atmospheric plasma spraying ytterbium oxide doped molybdenum silicide coating Ceram. Int. 46 6723–32
[29] Wang C C, Li K Z, He D Y and Shi X H 2020 Oxidation behavior and mechanism of MoSi2–Y2O3 composite coating fabricated by supersonic atmospheric plasma spraying Appl. Surf. Sci. 506 144776
[30] Yue G, Guo X P and Qiao Y Q 2020 Study on the diffusion barrier effect of WSi2 layer at the MoSi2/Nb–Ti–Si-based alloy interface Corros. Sci. 163 108299
[31] Wen S H and Sha J B 2019 Improvement of ‘Pest’ resistance of MoSi2 intermetallic compound at 500 °C and 600 °C via addition of B fabricated by spark plasma sintering Oxid. Met. 92 243–57
[32] Carolin Z, James S K L G, Verena M K, Steffen N, Mathias G and Sandra K K 2019 Low temperature deformation of MoSi2 and the effect of Ta, Nb and Al as alloying elements Acta Mater. 181 385–98
[33] Ingemarsson L, Hellström K, Johansson L G, Svensson J E and Halvarsson M 2011 Oxidation behaviour of a Mo(Si, Al)2-based composite at 1500 °C Intermetallics 19 1319–29
[34] Hou S X, Liu Z D, Liu D Y and Li B R 2012 Effect of alloying with Al on oxidation behavior of MoSi2 coatings at 1100 °C Surf. Coat. Technol. 206 4466–70
[35] Jiang L W, Wu M L, Shi P and Zhang C H 2019 The effect of Al and Cr elements on the oxidation resistance of MoSi2 via first-principles calculation Prog. Nat. Sci.- Mater. 29 65–70
[36] Hu D, Fu Q G, Zhou L, Zhang Y and Zhang G P 2020 Stress design of a laminated MoSi2/Cr coating under particle impact and high temperature environment Ceram. Int. 46 10696–703
[37] Fan Q K, Chen C, Fan C L, Liu Z, Cai X Y, Lin S B and Yang C L 2021 Ultrasonic suppression of element segregation in gas tungsten arc cladding AlCoCuFeNi high-entropy alloy coatings Surf. Coat. Technol. 420 127364
[38] Xu J, Wu J D, Li Z Y, Munroe P and Xie Z H 2013 Mechanical properties of Cr-alloyed MoSi2-based nanocomposite coatings with a hierarchical structure J. Alloys Compd. 565 127–33
[39] Wang C M, Yu Y, Yu J X, Zhang Y, Wang F C and Li H D 2020 Effect of the macro-segregation on corrosion behavior of CrMnFeCoNi coating prepared by arc cladding J. Alloys Compd. 846 156263