

CHARACTERIZATION AND OXIDATION BEHAVIOR OF SILICIDE COATING ON MULTIPHASES MO-SI-B ALLOYS

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ABSTRACT

Mo_{ss}-based Mo-Si-B multiphase alloys possess improved fracture toughness compared to its single-phase silicide counterparts (MoSi₂, Mo₅Si₃ or T2) without sacrificing high temperature strength, but they degrade rapidly in an oxidizing environment at elevated temperature. In the present study, MoSi₂ coating was applied to protect Mo_{ss}-based alloy from high temperature oxidation via pack cementation. Boron-modified MoSi₂ coating was also produced in an attempt to enhance the oxidation resistance of MoSi₂ coating via co-deposition of B and Si, using a two-step process. Isothermal and cyclic oxidation tests on coated Mo-4.3Si-1.1B alloy were performed at 1100°C and 1600°C, respectively up to 200 hours. The MoSi₂ coating provide enough protection from oxidation in both static and cyclic condition at 1100°C, while it degraded after ten hours by forming T1 (Mo₅Si₃B_x) phase at 1600°C via inter-diffusion between coating and substrate. The coating lifetime of MoSi₂ was limited by the Si depletion by diffusing into substrate. The Additions of boron into MoSi₂ did not enhance the oxidation resistance as boride phases (MoB or Mo₂B₃) do not slow the diffusion of Si to substrate to stabilize MoSi₂ or Mo₅Si₃.

INTRODUCTION

Molybdenum borosilicides have been investigated as a candidate material capable of service temperatures much higher than 1100°C. Two specific alloy systems have received considerable interests from the scientific community for high temperature applications. The first one, which was pioneered by Akinc and his co-workers[1], consists of three intermetallics alloys, Mo₅Si₃, the T2 phase Mo₅SiB₂ and the A15 phase Mo₃Si. They exhibit excellent oxidation resistance and creep strength up to 1600°C. The boron addition is critical for providing the observed oxidation resistance due to formation of low viscosity borosilicate glass layer that flows and seals the porous scale. However, these alloys also have low fracture toughness, and the thermal expansion anisotropy of the T1 phase make these alloys susceptible to thermal stress induced microcracking[2]. These deficiencies in mechanical behavior can be improved by moving towards the Mo-rich portion of the systems [3-8]. The second alloys, incorporates the bcc-Mo phase to impart some ductility and fracture toughness to a three-phase microstructure containing Mo₃Si and Mo₅SiB₂ (T2) along with Mo_{ss}. The Mo_{ss} phase can improve the room and high temperature fracture toughness significantly depending on its volume fraction and its distribution [6, 7]. However it presents a challenge in achieving adequate oxidation resistance as Mo₅Si₃B_x-based alloys do. The oxidation resistant phase of these alloys is believed to be T2 phase (Mo₅SiB₂) yet, its high boron content results in a borosilicate glass with a much low viscosity than that formed with the T1 phase (Mo₅Si₃B_x) leading to excessive volatility of MoO₃ through the scale, contributing to unacceptable metal recession rates above about 1300°C [9, 10]. Schneibel et al. [11] explored designing a bcc-Mo containing composite to balance acceptable oxidation resistance with adequate mechanical behavior with limited success.

An emerging consensus is to protect the Mo_{ss}-based alloys with an oxidation resistant coating [12, 13]. One approach for developing an oxidation resistant coating is to deposit a silicon-rich phase, such as the MoSi₂ or T1-based alloy, onto the surface of the component. The halide activated pack cementation (HAPC) process has been successfully employed to deposit MoSi₂ onto a two-phase T2/Mo(ss) eutectic alloy by Ito et al.[13], and Mo-3Si-1B alloy by Sakidja et al. [12]. Although the steady-state oxidation rate of the coated alloy was nearly equal to that of MoSi₂ for up to 50 hours at 1300°-1500°C, the MoSi₂ layer was partially transformed to T1 phase, and the long term effect of this microstructural change on the oxidation resistance of the coating was not investigated. The present

work investigates the feasibility of using the HAPC process to form oxidation resistant diffusion coatings on the Mo_{ss}-based Mo-4.3Si-1.1B (wt.%) alloy. Coating process development, oxidation performance and interdiffusion behavior of the coated alloy will be discussed.

EXPERIMENTAL

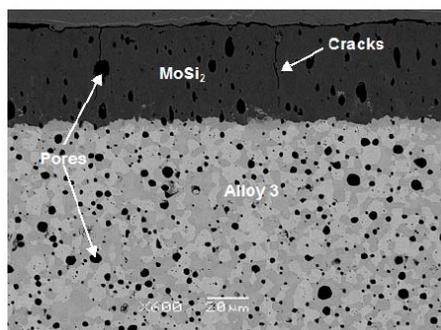
The nominal composition of the substrate alloy selected for this study is Mo-4.3 wt.%Si-1.1wt.%B (all compositions are in weight percent unless stated otherwise). These ternary alloys contain Mo₃Si, Mo₅SiB₂ (T2) and α -Mo (Mo solid solution), and were fabricated by either drop-casting or sintering powder compacts. Both drop-cast and sintered alloys were cut into small coupons and polished with 600-grit SiC paper, then ultrasonically cleaned in acetone and ethanol. The halide-activated pack cementation process was employed to deposit silicon and/or boron onto the substrate samples. The components in pack cementation include: the masteralloy (i.e. a powder of the element or elements to be deposited on the surface of the parts, such as Si and/or B), a halide activator (e.g. NaF), and an inert filler powder (e.g. Al₂O₃). Three kinds of pack cementation processes were employed in this study: i) Si deposition only, ii) co-deposition of Si and B, and iii) two-step boronizing and siliconizing. The deposition process was carried out at 900°C or 1000°C for 12-48 hours in flowing Ar atmosphere.

Isothermal oxidation tests on coated samples were conducted in a tube furnace in flowing dry air at 1100°C or 1600°C up to 400 hours. Thermal cycling exposure was also carried out in air at 1100°C. The thermal cycle consists of heating to 1100°C at 20°C/min, holding for 24 hours and cooling in 5 min to room temperature. Mass change was continuously recorded after every cycle. The as-deposited, annealed and oxidized samples were examined by X-ray diffraction (XRD, Scintag XDS 2000, Cupertino, CA) to identify the phases formed. Microstructural features of the surface and cross-section of the samples were examined by scanning electron microscopy using backscattered electron imaging (SEM/BSE, JEOL, JSM 6100, Peabody, MA) and energy dispersive spectroscopy (EDS, Oxford Instruments, Valley, CA).

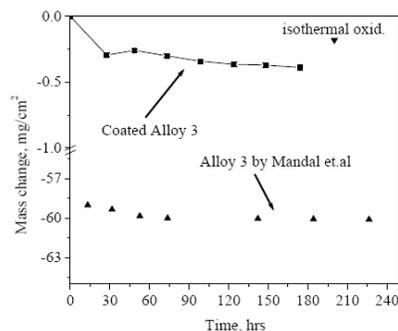
RESULTS AND DISCUSSION

Silicide Coating

Fig.2a shows a typical cross-section of the silicide coating formed on sintered alloy 3 (Mo-4.3Si-1.1B) coupon after 48 hours pack cementation at 1000°C in an Si pack. The EDS and XRD analysis confirmed that the coating was MoSi₂ with the C11_b structure. A uniform coating layer about 40 μ m in thickness formed on the substrate. At least 10 measurements were taken and the average thickness of MoSi₂ layer was determined. Growth of MoSi₂ layer was found to be parabolic with respect to deposition time with a corresponding rate constant of 8×10^{-11} cm²/s at 1000°C. This value compares very well with the intrinsic parabolic growth rate constant of MoSi₂ obtained from Si/Mo diffusion couple (3.91×10^{-10} cm²/s) [14]. The inward-diffusion of silicon is thought to be the rate-controlling step. None of the Mo₅Si₃, Mo₃Si or T2 (Mo₅SiB₂) phases were detected between the MoSi₂ layer and the substrate. This result is in agreement with the kinetic studies of Mo/Si diffusion couple as well, [14] that the intrinsic growth rates of Mo₅Si₃ and Mo₃Si are slower than that of MoSi₂ about two or three orders of magnitude at 1000°C. It should be noted the MoSi₂ coating of the as-deposited alloy was always cracked at the corners and edges of the substrate, and the perpendicular microcracks were extending to the surface were also observed (see Fig2a).



(a)



(b)

Figure 1 a. Micrographs of silicide coating growing on sintered Mo-4.3Si-1.1B alloy by a NaF activated pack; b. Mass change of a pack cemented alloy after isothermal and cyclic oxidation at 1100°C in dry air

The oxidation behavior of the coating was assessed by measuring the weight change as a function of exposure time. Fig.2b show that the weight gain data at 1100°C for pack cemented alloy. For comparison, the mass change of uncoated Mo-4.3Si-1.1B alloy reported by Mandal et. Al [15] at 1100°C was also included in this plot. Only a slight weight loss of about 0.2 mg/cm² was observed after oxidation at 1100°C for 200 hrs. Even after 8 cycles (total 192 hours), weight loss was less than 0.5 mg/cm², suggesting that the microracks formed by pack cementation process was sealed by silica glass and had no obvious detrimental effect on the oxidation behavior of MoSi₂ coating during exposure to air at 1100°C. For comparison, Mandal et. al.[15] reported the uncoated Mo-4.3%Si-1.1%B alloy suffered a significant weight loss of more than -60 mg/cm² at 1100°C for 200 hrs, suggesting a loss of volatile MoO₃. Clearly, MoSi₂ coating significantly suppressed the rapid oxidation of alloy 3. The cross-section of oxidized alloy is shown in Fig.3a. No significant oxidation was observed in the coating or substrate. Only a thin silica glass formed at the surface. A very thin Mo₅Si₃ layer was observed between the silica scale and MoSi₂ coating due to selective oxidation of Si. In addition, a Mo₅Si₃ layer below the MoSi₂ coating less than 20µm thick was observed as a result of interdiffusion between coating and substrate.

Oxidation in air at 1600°C for two hours results in a small weight loss of about -0.1 mg/cm², but significant changes in the microstructure (see Fig.3b). The microstructure of the coating depicts three layers: i) an outer layer about 25µm in thickness comprising mixed MoSi₂/T1 phases, ii) an intermediate layer about 50µm in thickness containing single T1 phase, and iii) a 10µm thick interlayer consisting of MoB and T2 phases. The cracks that penetrated through the outer MoSi₂ layer were arrested at the intermediate T1 layer and sealed by the silica glass.

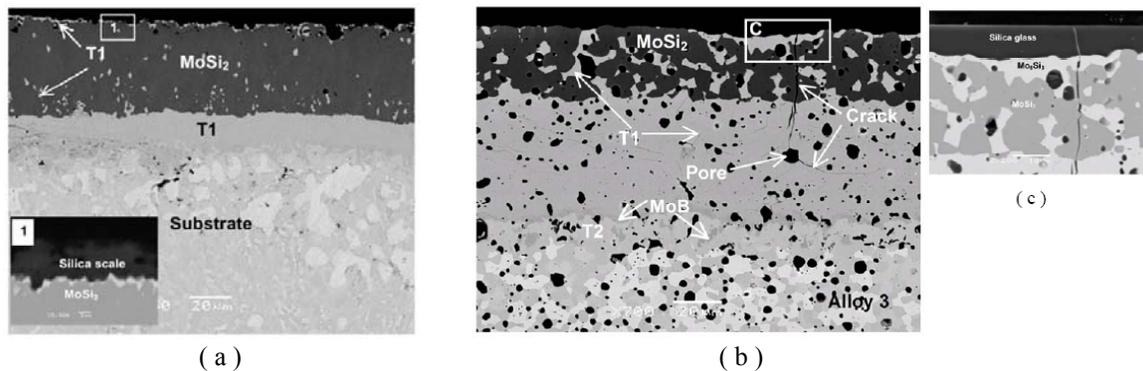


Figure 2 Micrographs showing cross-section of silicide coating growing on sintered Mo-4.3Si-1.1B alloy by a NaF-activated pack after isothermal oxidation in dry air: (a) at 1100°C for 200hrs, (b) at 1600°C for 2 hours.

Although the transformation rate from MoSi₂ to T1 layer was not experimentally determined, annealing of the sample in Ar confirmed that the transformation of a MoSi₂ coating, is less than 12hrs at 1600°C. Once MoSi₂ layer is completely transformed to T1, the coating oxidized rapidly since the T1 and MoB/T2 multilayer structure do not form a protective silica layer. In fact, the coated alloy was completely oxidized after exposure to air at 1600°C for 50 hours.

Borosilicide Coating

The rapid loss of the MoSi₂ coating is a result of preferential silicon diffusion into substrate which leads to the growth of T1 layer. Since the oxidation behavior of T1-based phase is strongly dependent on boron content, undoped T1 (i.e., Mo₅Si₃) exhibits catastrophic mass loss above 1000°C due to formation of a porous oxide scale. A small amount of boron added to Mo₅Si₃ results in a non-porous, protective scale. The B addition allows viscous flow to close submicron scale porosity. Meyer and Akinc [16] studied the isothermal oxidation of several B-doped Mo₅Si₃ alloys around Mo₅Si₃ phase field at 1450°C and concluded that a minimum boron content is somewhere between 0.14 wt.% and 0.91 wt.% required in order to form a protective scale on Mo₅Si₃-based materials. This boron level is definitely exceeds the solubility of B in Mo₅Si₃. Indeed, the oxidation resistant Mo₅Si₃-based alloys studied to date were always multiphase containing at least a small amount of MoSi₂, T2 or MoB phases. Therefore, the boron-modified silicide diffusion coatings were developed via pack cementation in order to address the poor

oxidation behavior of T1 interlayer. Two approaches were employed: co-deposition of B and Si onto alloy 3 and sequential deposition of B followed by Si.

Co-Deposition Of B And Si

The SEM micrograph in Fig.4a shows the cross-section of a multilayered borosilicide coating formed on sintered Mo-4.3Si-1.1B alloy after 48 hours co-deposition of Si and B in a pack with Si/B=9 (#3) at 1000°C. Instead of single MoSi₂ layer observed in silicon only coating, the co-deposited coating consists of three layers: i) an 20µm thick MoSi₂ outer layer, ii) a 30µm thick intermediate layer consisting of MoB needles and particles in a MoSi₂ matrix. The presence of MoB was confirmed by XRD by carefully polishing away the top MoSi₂ layer, iii) a 10µm thick inner layer containing mostly T2 (Mo₅SiB₂) phase with dispersed MoB particles. Thus, MoB phase was successfully incorporated into the coating by incorporating B in the pack mixture. The distribution of boron in the coating suggested that diffusion of B in MoSi₂ layer is much faster than Si.

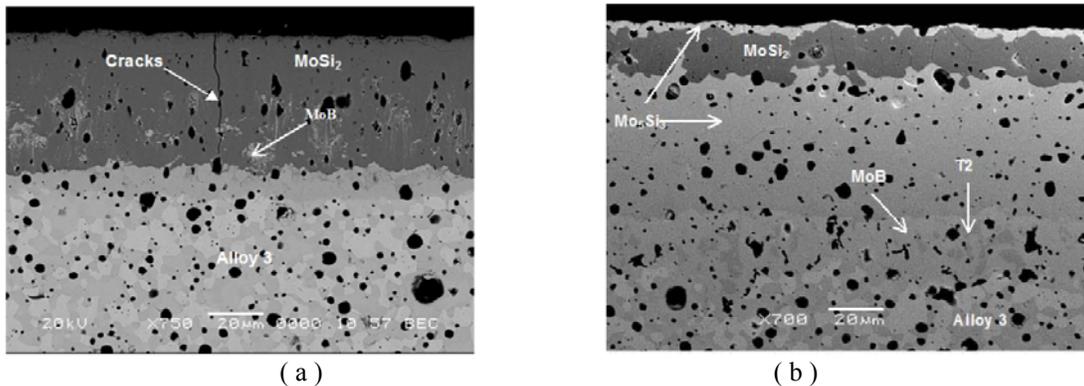


Figure 3 SEM micrographs of B-modified silicide coating on sintered Mo-4.3Si-1.1B alloy produced by co-deposition of B and Si: (a) as-deposited, (b) after isothermal oxidation in dry air at 1600°C for 2 hours.

Both short-time and long-time isothermal oxidation tests were run on the co-deposited samples. A weight loss of less than -0.1 mg/cm^2 was observed after oxidation at 1600°C for two hours in air, while the sample is totally oxidized after 50 hrs exposure. Fig.4.b shows back-scattered electron (BSE) images of co-deposited alloy after short-time oxidation. No obvious oxygen attack into substrate through cracks was observed, which indicated that cracks were sealed by borosilicate glass and were not the cause of the long-time oxidation failure. The MoSi₂ coating was partially transformed into T1 phase and an interlayer consisting of MoB particles-dispersed T2 matrix with was observed. The interlayer has the same phase constitutions (T2+MoB) as that in Si only coating. It is thicker (25µm vs. 15µm) perhaps in part due to the incorporation of boride phases into MoSi₂ coating. According the Mo-Si-B ternary phase diagram, MoB is can co-exist with MoSi₂ and Mo₅Si₃ phases. However, careful XRD and SEM analysis after removing the top layer showed no evidence of MoB phase in either MoSi₂ or Mo₅Si₃ phases, suggesting that MoB must have reacted with Si to form T1 as silicon diffuses into the substrate, as will be discussed later. The MoSi₂ layer was completely transformed into T1 phase after annealing at 1600°C for twelve hours. It is presumed that poor oxidation resistance of Mo₅Si₃ layer formed by interdiffusion between the coating and substrate is responsible for the degradation.

Two-Step B+Si Coating

Fig.5 shows the micrographs of Mo-4.3Si-1.1B alloy after boronizing. A complex two-layer diffusion microstructure was developed: a ~10µm thick outer Mo₂B₅ layer with dispersed MoB particles, a ~30µm thick network of T2 and MoB mixed inner layer. Apparently, MoB in T2/MoB inner layer formed from reaction of B with Mo phase in the substrate, and T2 evolved from reaction of B with Mo₃Si. Closer examination of the interface between the coating/substrate by SEM/EDS revealed fine T2 particles, which were formed within the MoSi₃ phase near the interface. Dark spots observed in the inner T2 layer were identified as MoSi₂ phase by EDS. The formation of MoSi₂ could occur if Si content exceeds the solubility limit in T2 phases as B reacts with Mo₃Si to form T2.

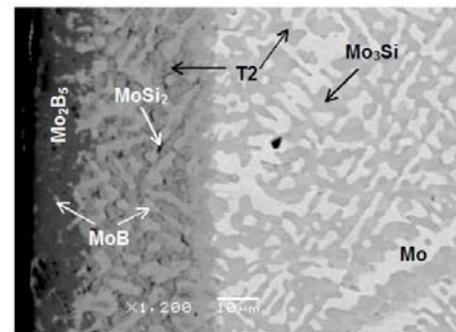


Figure 4 SEM micrographs of cast Mo-4.3Si-1.1B alloy pack cemented in a B pack

Fig.6a shows the cross-sectional microstructure of as-prepared and annealed two-step coating (B+Si). After two step pack cementation (boronizing and siliconizing), Mo_2B_5 top layer formed is totally converted into MoSi_2 and a $\sim 12\mu\text{m}$ thick MoSi_2 layer is formed. A $40\mu\text{m}$ thick T2+MoB intermediate layer is observed between MoSi_2 and substrate. The thickness of this intermediate layer is similar to that of B-packed alloy 3 (Fig.5). It implies that when $\text{Mo}_2\text{B}_5/\text{MoB}$ transformed into MoSi_2 by Si cementation followed by B diffuse through MoSi_2 since the solubility of boron in MoSi_2 is negligible.

After annealing at 1400°C for 24 hours, the MoSi_2 phase is completely transformed into T1, and the T2 fraction in the T2/MoB layer increased. Unlike the as-packed coating in which the T2/MoB interlayer consists of MoB matrix with interconnected T2 phase, the interlayer in the annealed coating consists of T2 matrix with isolated MoB grains. Some Mo_5Si_3 particles were also observed in the T2 phases.

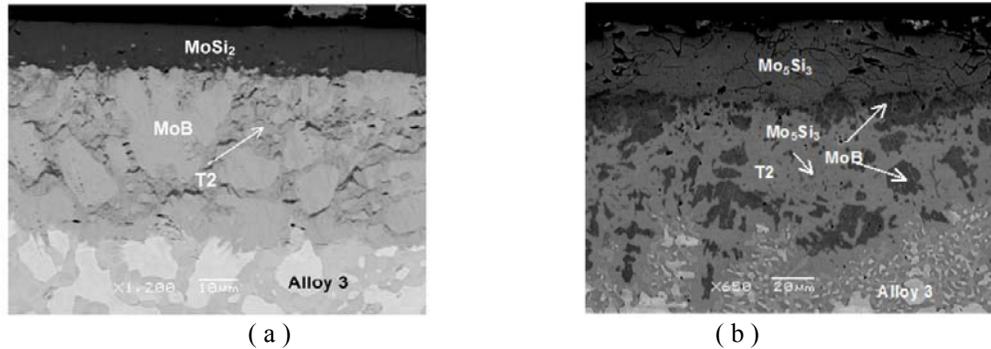


Figure 5 SEM micrographs of cast Mo-4.3Si-1.1B alloy by boronizing in a B pack (#2) followed by siliconizing in a Si pack(#1): (a) as packed coating, (b) annealed at 1400°C for 24 hours

Evaluation Of Silicide And Borosilicide Coating

The excellent high temperature strength and oxidation resistance qualify MoSi_2 as protective coating for Mo-based alloys. Similar studies by Ito et al.[13, 17] on Mo-9Si-18B (at.%) alloy and Sakidja et al.[12] on Mo-14.2Si-9.6B at.% alloy revealed. Two significant challenges for future high temperature application still remain: i) thermal stresses generated by coefficient of thermal expansion (CTE) mismatch at the coating-substrate or coating-oxide interface, and the large CTE anisotropy of T1 may induce cracks during process. Although these cracks may be sealed by silica (or borosilicate) glass at high temperature, it may still cause degradation of coating under thermal cycling, ii) the rapid diffusion of Si from MoSi_2 coating results in the formation of the T1 phase which does not provide oxidation protection for the substrate.

Thermal Stress

MoSi_2 goes through ductile-to-brittle transition at approximately 1000°C . Thermal stress resulting from the CTE mismatch between the MoSi_2 coating and substrate can cause cracks in the coating if they reach or exceed a critical value, i.e., the strength of MoSi_2 . Since the tensile strength of MoSi_2 is much lower than its compressive strength (275 MPa vs. more than 1378 MPa)[18], tensile stresses are particularly damaging and will promote transverse microcracking in the coating, as observed in this study.

Using the bulk CTE as and $\Delta T=975^\circ\text{C}$ (cooling the sample to room temperature from 1000°C), the thermal stresses developed in the MoSi_2 coating are 1041, 709 and 520MPa with substrates Mo, Mo_3Si and Mo_5SiB_2 , respectively. These stresses definitely exceed the tensile strength of MoSi_2 (275MPa). As shown Fig.2a and Fig.4a, the transverse microcracking was observed in the as-packed MoSi_2 coating no matter how slowly they were cooled. Fortunately, the present oxidation experiments showed that no significant oxidation through cracks ($\Delta m < 1\text{mg}/\text{cm}^2$) occurred since the silicate glass formed by oxidation may have sealed them. Similar results were also reported by Ito et al.[13]. They indicated the presence of microcracks in the as-deposited MoSi_2 coating on T2/ Mo_{ss} substrate; however, steady-state weight gain with mass gain of less than $2\text{mg}/\text{cm}^2$ was observed after 50 hours oxidation at 1500°C . It

should be noted that the MoSi_2 were not completely transformed into T1 phases after 50 hours exposure in Ito's experiments, which provide the reservoir of Si for the formation of continuous silicate glass.

Thermodynamic Stability

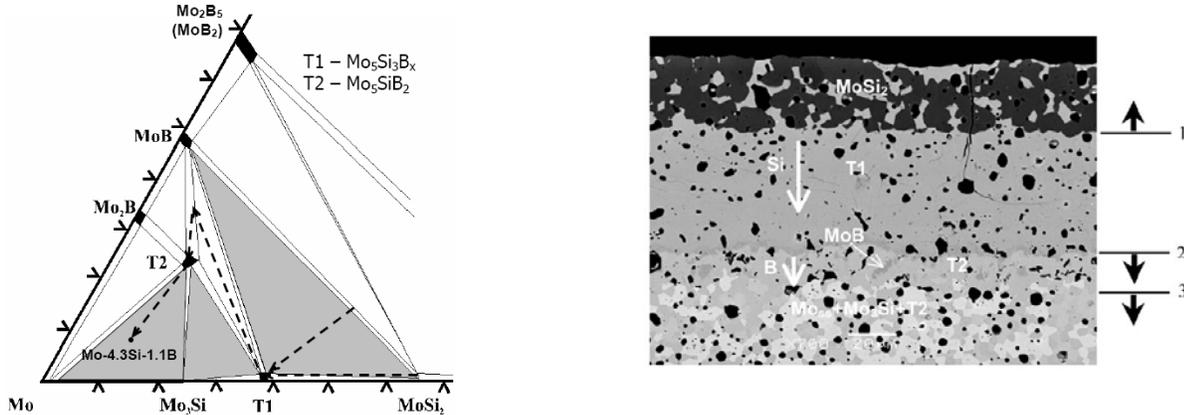
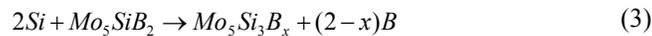
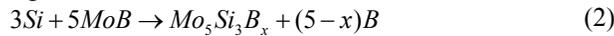


Figure 6 Schematic description of diffusion path showing reaction between MoSi_2 coating and three-phase ($\text{Mo}+\text{Mo}_3\text{Si}+\text{T}_2$) substrate ,

From the microstructural features, the diffusion paths for silicide and boron-modified silicide coatings on multiphase alloy 3 can be drawn on Mo-Si-B ternary phase diagram (Fig.7). A diffusion zone with Mo_5Si_3 (T1) and $\text{MoB}+\text{T}_2$ two-phase layer was observed in both cases whether the coating contains boride phases or not. The diffusion reaction can be described as followed: MoSi_2 decomposes into T1 ($\text{Mo}_5\text{Si}_3\text{B}_x$) and Si by Equation (1) as in MoSi_2/Mo and MoSi_2/T_2 diffusion couple. The interface 1 shifts toward MoSi_2 phase and the Si atoms diffuse through T1 to interface 2, at which additional T1 phase is formed by the following reactions:



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Since solubility of boron in T1 phase is negligible, the excess boron atoms must diffuse toward interface 3 to form boron-rich phases such as: T2 and MoB since B has limited solubility in T2 phase. Therefore, the lifetime of silicide coating is limited by the growth rate of T1 layer, i.e. conversion of MoSi_2 into T1.

In B/Si co-deposition coating, the diffusion path did not change even though the composition of the coating moved up to the B-rich side along the tie line between MoB and MoSi_2 in the ternary Mo-Si-B phase diagram. MoB did not stabilize the MoSi_2 phase; rather it reacted with Si to form T1 phase and release B atoms. The excess B diffuses to coating/substrate interface to form borides by reacting with Mo and Mo_3Si .

For the MoSi_2 -based coating, the lifetime is limited by the growth rate of T1 layer. Fig.8 shows the apparent growth rate of Mo_5Si_3 layer for MoSi_2/Mo diffusion couple. The data represents the intrinsic growth rate of Mo_5Si_3 layer. Although there is some scatter in the data in part due to difference in sample preparation, the values are on the same order magnitude. The apparent growth rates of Mo_5Si_3 layer in the MoSi_2/T_2 diffusion couple and MoSi_2 coating on $\text{T}_2+\text{Mo}_{\text{ss}}$ are also included. The growth rates of Mo_5Si_3 in ternary Mo-Si-B system are slightly lower than that of MoSi_2/Mo diffusion couple presumably due to the existence of T1+MoB two-phase layer. The lifetime of MoSi_2 coating on three-phase Mo-Si-B alloy can be estimated by considering conversion rate of MoSi_2 to T1. Fig.9 shows that estimated lifetime as a function of exposure temperature assuming that the initial thickness of MoSi_2 layer is $100\mu\text{m}$. The maximum and minimum lifetimes are calculated based highest and lowest data in growth rate of Mo_5Si_3 layer in Fig.8a. The coating can last more than 1000 hours with service temperature below 1300°C , while it will lose protection less than hundred hours above 1500°C due to rapid interdiffusion.

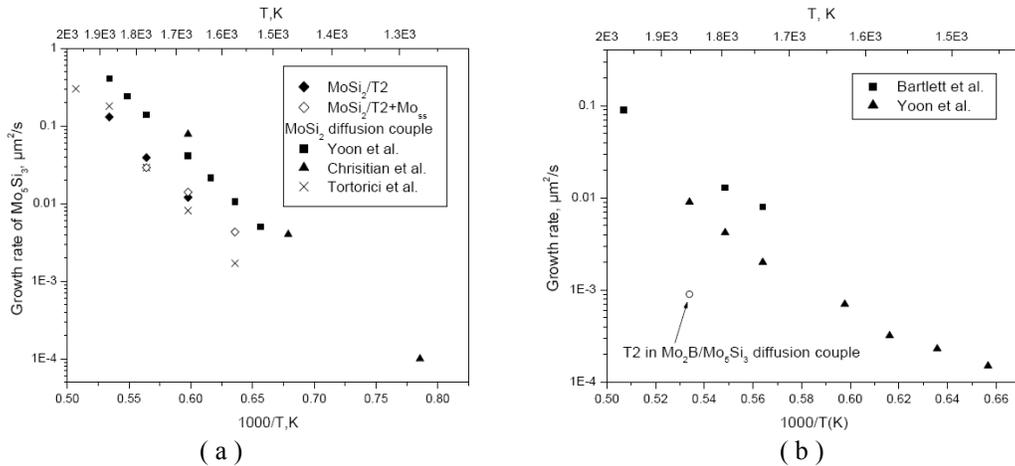


Figure 7 Arrhenius plot of parabolic growth rate as a function of the reciprocal temperature for a) Mo_5Si_3 and b) Mo_3Si .

Strategies Of Extending Lifetime Coating

MoSi_2 -based coating was impaired above 1300°C by the formation of poor oxidation resistant Mo_5Si_3 interlayer due to rapid interdiffusion. No alloy has been identified as a diffusion barrier for MoSi_2/Mo couple. Addition of refractory alloying elements such as W and Nb can slow the growth rate of $(\text{Mo},\text{M})_5\text{Si}_3$ significantly [19], but not enough to last for several hundred hours above 1500°C . Thus new coating design strategy needs to be considered. Thom et al. [20, 21] reported that Mo-13.4Si-2.6B (T1+MoB+ MoSi_2) and Mo-9.9Si-1.4B (T1+T2+ Mo_3Si) alloys possess excellent oxidation resistance up to 1600°C . Thus, if the coating composition was shifted to Mo-rich regions, such as T1+T2+ Mo_3Si three phase region, the Si diffusion inward will result in the formation of Mo_3Si or T2 interlayer instead of T1 according to Mo-Si-B ternary phase diagram. The intrinsic growth rate of Mo_3Si phase is about at least one order of magnitude lower than that of Mo_5Si_3 at the temperature of $1000\text{--}1700^\circ\text{C}$ as shown in Fig. 8. And this can reduce the depletion rate of Si from silicide coating, therefore extend the lifetime of coating.

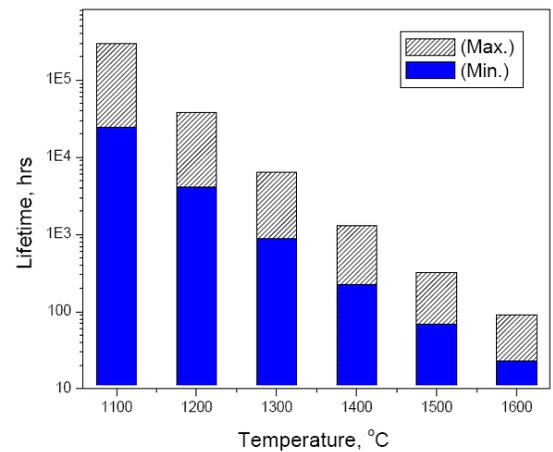


Figure 9. Estimated lifetime of MoSi_2 -based coating on three-phase ($\text{Mo}_5\text{Si}_3+\text{Mo}_3\text{Si}+\text{T2}$) alloy

SUMMARY

MoSi_2 -based silicide diffusion coating was successfully deposited onto Mo_{ss} -based multiphase Mo-Si-B alloy via pack cementation, the coating process, oxidation behavior and interdiffusion behavior were investigated, and the results obtained are summarized as follows:

1. In the pack siliconizing coating, a MoSi_2 layer was developed on the three phase substrate ($\text{Mo}+\text{Mo}_3\text{Si}+\text{Mo}_5\text{Si}_3$). After annealing or exposure to air at high temperature, MoSi_2 was transformed to T1 phase, which possesses poor oxidation resistance at elevated temperature.
2. Boride phases (MoB and Mo_2B_5) were successfully added to MoSi_2 coating either by co-deposition of B and Si or by a two-step process, and the concentrations of boride phases can be controlled by adjusting the Si/B ratio in the pack mixture. However, those boride phases cannot be stabilized with either MoSi_2 or Mo_5Si_3 phases after exposure to high temperature. MoB phase was consumed by the formation of Mo_5Si_3 as silicon diffuse downward and the expelled boron diffused downward into substrate to form new borides. As a result, a diffusion zone with $\text{Mo}_5\text{Si}_3/(\text{T2}+\text{MoB})$ layers formed.

3. Both silicide and boron-silicide coating can prevent the oxidation of Mo-4.3Si-1.1B alloy at 1100°C in both static and cyclic conditions and estimated to be lasted for thousand of hours, while the coating lost their protection at 1600°C due to rapid interdiffusion between MoSi₂ and substrate, which leads to formation of poorly oxidation resistant T1 phase. The lifetime of MoSi₂-based coating is limited by Si depletion through the formation of T1 phase.
4. New coating design approach was proposed based on the diffusion data. T1-based Mo-Si-B coating will reduce the Si depletion rate from the surface by formation of slow growing Mo₃Si or T2 layer without sacrificing the oxidation resistance of the coating, therefore extending the coating lifetime above 1500°C.

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