Synthesis and properties of MoAlB composites reinforced with SiC particles

Weiwei ZHANG^a, Shibo LI^{a,b,*}, Shuang WU^a, Boxiang YAO^a, Shukai FAN^c,
Guoping BEI^c, Wenbo YU^{a,b}, Yang ZHOU^{a,b}, Ying WU^d, Sun-An DING^d

^aCenter of Materials Science and Engineering, School of Mechanical and Electronic Control Engineering,
Beijing Jiaotong University, Beijing 100044, China

^bResearch Center of Rail Vehicles Safety Monitoring and Health Management,
Beijing Jiaotong University, Beijing 100044, China

^cChina Porcelain Fuchi (Suzhou) High Tech Nano Materials Co., Ltd., Suzhou 215100, China

^dSchool of Microelectronics, Southern University of Science and Technology, Shenzhen 518055, China

Received: September 8, 2021; Revised: September 19, 2021; Accepted: October 1, 2021

© The Author(s) 2021.

Abstract: Novel MoAlB composites reinforced with 5–15 vol% SiC have been firstly prepared and characterized in the present study. The SiC reinforcement is stable with MoAlB at a sintering temperature of 1200 °C in Ar. The 5 vol% SiC/MoAlB composite exhibited improved mechanical properties and enhanced oxidation resistance. A flexural strength of 380 MPa and a Vickers hardness of 12.7 GPa were achieved and increased by 24% and 51%, respectively, as compared with those for MoAlB, indicating the enhanced strengthening effect of SiC. Cyclic oxidation tests at 1200 and 1300 °C for 10 h in air showed that the 5 vol% SiC/MoAlB composite has better oxidation resistance than MoAlB due to the formation of a dense and continuous scale composed of Al₂O₃ and SiO₂, which prevents the oxygen inward diffusion and the evaporation of oxides. We expect that the general strategy of second phase reinforcing for materials will help to widen the applications of MoAlB composites.

Keywords: SiC/MoAlB composite; mechanical properties; oxidation; microstructure

1 Introduction

MoAlB is an attractive ternary boride in MAB phase family (where M is a transition metal, A is aluminium or zinc, and B is boron [1]) not only due to its ease of fabrication and densification at relatively lower temperatures (1050–1200 °C) but also to its excellent high temperature oxidation resistance as compared with the vast majority of binary transition metal

borides. The binary transition metal borides generally require high temperatures above 1700 °C to achieve full density, but have poor oxidation resistance at temperatures above 1000 °C [2].

MoAlB, as the most studied MAB phase, has been widely investigated from theoretical simulations [3–5] to experimental studies, and exhibits attractive mechanical properties, high temperature properties, radiation tolerance, and ablation resistance [6–12]. So far, MoAlB as the only one in the MAB phase family has been demonstrated with better oxidation resistance than other Al-containing MAB phases (such as Fe₂AlB₂ and Cr₂AlB₂) at temperatures below 1300 °C due to

* Corresponding author.

E-mail: shbli1@bjtu.edu.cn

the formation of a dense and continuous α -Al₂O₃ layer [13–16]. The oxidation resistance of MoAlB is even better than that of Ti₂AlC and Cr₂AlC MAX phases at 1100 °C [17–19]. For example, the oxidation rate constant K_c of MoAlB is about 7.1×10^{-23} m³/s at 1100 °C [8], lower than 1.0×10^{-21} – 1.8×10^{-21} m³/s for Ti₂AlC [17]. However, increasing oxidation temperature leads to the rapid mass gains of MoAlB. To further improve its oxidation resistance, the replacement of some Al by Si in MoAlB to form a Mo(Al,Si)B solid solution has been designed because the dissolved Si can be oxidized to SiO₂ which retards the inner diffusion of O upon oxidation. The Mo(Al,Si)B solid solution exhibited better oxidation resistance than its natural counterpart [19]. In the temperature range of 1200–1400 °C, the mass gain and the scale thickness of Mo(Al,Si)B are lower than those of MoAlB [19]. The above results confirm that Si can effectively improve the oxidation resistance of MoAlB. However, the solubility of Si in MoAlB is limited, with the maximum solubility of ~0.91 at% Si [20], causing the difficult study of the influence of Si content on the oxidation behavior of MoAlB.

Another facile route to enhance the oxidation resistance of MoAlB is the incorporation of ceramic particles. Among ceramic particles, SiC is preferred to reinforce MoAlB due to the following two reasons. First, SiC has high hardness and excellent oxidation resistance. Second, SiC has been proved to be a good reinforcement in MAX composites. The incorporation of SiC in Ti₃SiC₂ matrix is one of the simplest yet effective approaches to prepare composites with greatly improved mechanical properties and high temperature oxidation resistance [21–26]. Up to now, to the best of our knowledge, there are no reports on the synthesis and characterization of SiC/MoAlB composites.

In the present study, the main purpose is to prepare SiC/MoAlB composites for the first time. The mechanical properties and oxidation resistance of composites were investigated. The phase composition and microstructure of the prepared composites were characterized.

2 Experimental

2.1 Material preparation

To prepare MoAlB samples, Mo (-300 mesh, 99.5% purity, General Research Institute for Nonferrous Metals GRINM, China), Al (-300 mesh, 99.5% purity,

Beijing Reagent Company, China), and B (-300 mesh, 99% purity, GRINM, China) powders with a molar ratio of Mo:Al:B = 1:1.3:1 were mixed for 10 h, and then pressureless-sintered at 1200 °C for 1 h in Ar atmosphere. The sintered samples were pulverized, and then sieved with a 200 meshed sieve to obtain MoAlB powders.

To prepare SiC/MoAlB composites, powders of SiC (an average size of ~28 µm, > 99% purity, GRINM, China) and MoAlB were mixed for 10 h, and then hot pressed at 1200 °C under 25 MPa for 1 h in Ar atmosphere. The volume contents of SiC are 5, 10, and 15 vol%.

2.2 Mechanical property measurement

The prepared SiC/MoAlB samples were cut into bars with different sizes by a wire electrical discharge machine. The bars were polished to 1 µm by diamond paste, cleaned with ethanol, and then dried in an oven at 50 °C for 4 h. The different-sized bars were used for mechanical properties and oxidation tests.

3 mm × 4 mm × 36 mm bars were used to measure the flexural strength by the three-point bending test in a WDW-100E compression machine (China). The span size and crosshead speed were 30 mm and 0.5 mm/min, respectively.

The Vickers hardness test was performed in a TH700 hardness tester under loads of 1–20 kg with a dwelling time of 15 s. Six measurements in different areas were performed for each sample to obtain an average value.

2.3 Oxidation test

3 mm × 4 mm × 10 mm bars were used to investigate the cyclic oxidation behavior in a TSK-5-14 high temperature tube furnace at 1200 and 1300 °C for 10 h in air. The weight gain was measured at the interval of 2 h. The weight change of the samples was measured using an analytical balance with an accuracy of 0.0001 g, and converted into a specific weight change per surface area. The oxidized samples were used to the following microstructure and phase characterization.

2.4 Characterization

The phase compositions of mixtures, hot-pressed samples before and after oxidation were analyzed by X-ray diffraction (XRD) analysis using an Ultima IV

diffractometer (Rigaku, Japan) with Cu K α radiation ($\lambda = 0.154$ nm) operated at 40 kV and 40 mA. The morphologies of mixture powders, polished and fractured surfaces of hot-pressed samples, and oxide scale were characterized with a ZEISS EVO 18 scanning electron microscope (SEM; Carl Zeiss SMT, Germany) equipped with an energy dispersive spectrometer (EDS) system.

For transmission electron microscopy (TEM) examination, focused ion beam (FIB) cross-section was prepared with a dual-beam FIB/SEM (FEI Scios, USA) by using a Ga⁺ ion source operating at 30 kV. A thin slice representing a cross-sectional cut perpendicular to the SiC/MoAlB boundary was analyzed by an FEI Talos F200X (FEI, USA) TEM with an operating voltage of 200 kV.

3 Results

3.1 Preparation and characterization of SiC/MoAlB composites

MoAlB composites reinforced with 5, 10, and 15 vol% SiC were prepared by hot pressing at 1200 °C under 25 MPa for 1 h in Ar atmosphere. Figure 1 presents the XRD results for the prepared composites. The composites are primarily composed of MoAlB and SiC, with a small amount of Al₃Mo. No new phases were found in the XRD patterns, which probably indicated that no reaction happened between SiC and MoAlB at the sintering temperature of 1200 °C. The back-scattered SEM micrograph (Fig. 2(a)) depicts the distribution of SiC particles (black color) with irregular shapes in the 10 vol% SiC/MoAlB composite. SiC particles with an average size of ~28 μm were homogeneously

distributed in MoAlB matrix (with sizes of less than 40 μm). Al₃Mo (light grey color in Fig. 2(a)) and Al₂O₃ (small black particles in Fig. 2(b)) as impurity phases appeared, which should be from the initial MoAlB powders. No Al₂O₃ peaks were detected in the XRD patterns (Fig. 1), possibly due to their amount below the detection limit of XRD. An enlarged SEM image, taken from the dashed rectangle area in Fig. 2(a), clearly shows the boundary areas between SiC and MoAlB particles (Fig. 2(b)). Neither new formed phases nor reaction layers could be detected in the boundary areas, confirming the thermal stability of SiC with MoAlB at 1200 °C.

TEM analysis was performed to further examine the microstructure of the 5 vol% SiC/MoAlB composite. Figure 3(a) shows the TEM analysis of a representative SiC/MoAlB phase boundary. No reaction zones are observed in the phase boundary. A high resolution TEM (HRTEM) image presents the lattice fringes of SiC and MoAlB (Fig. 3(b)). The measured interplanar

Fig. 1 XRD patterns of (a) 5 vol%, (b) 10 vol%, and (c) 15 vol% SiC/MoAlB composites.

Fig. 2 Back-scattered SEM micrographs of the polished surface of 10 vol% SiC/MoAlB: (a) a low magnification image and (b) a high magnification image taken from (a).

Fig. 3 (a) TEM image of SiC/MoAlB and (b) HRTEM image of the zone marked with a dashed rectangle in (a).

spacing is ~ 0.1822 nm corresponding to the (102) plane of SiC and 0.704 nm corresponding to the (020) plane of MoAlB. The HRTEM image reveals that the interface is clean and continuous, without new phases or amorphous phases at the interface, further confirming the stability of SiC with MoAlB at the sintering temperature.

3.2 Mechanical properties

The measured mechanical properties as a function of reinforcing phase content are presented in Fig. 4. A flexural strength of 380 MPa and a Vickers hardness of 12.7 GPa have been successfully achieved in the 5 vol% SiC/MoAlB composite and increased by 24% and 51%, respectively, as compared with 306 MPa and 8.4 GPa for MoAlB. However, both the strength and the hardness decrease with the increase of SiC content (Figs. 4(a) and 4(b), respectively). The deterioration of the mechanical properties should be caused by the decreased relative density. Under the hot pressing conditions of 1200 °C with 25 MPa, the 5 vol% SiC/MoAlB composite has a relative density of $\sim 92.6\%$,

close to 93% for MoAlB material, whereas the 15 vol% SiC/MoAlB composite has a low relative density of 83.8%. Further increasing hot pressing temperature to 1250 °C contributes little to the increase in the density of SiC/MoAlB composites.

The fracture surface demonstrates that the fracture mode is mainly transgranular (Fig. 5(a)). The cracks are deflected in the MoAlB grains due to their nanolaminated structure. The nanolaminated structure of MoAlB can prolong the crack propagation paths, consuming more energy as the cracks propagate in the grains, and thus endowing MoAlB with good damage tolerance and thermal shock resistance [27]. Figure 5(b) further illustrates a crack propagation path emitting from an indentation corner. It can be found that the hard SiC particles play roles of “bridging”, “pinning”, and “deflecting” cracks in the crack propagation resistance.

The above results confirm that the incorporation of 5 vol% SiC reinforcement in MoAlB is preferred and its strengthening effect is obvious. Therefore, the following study mainly focused on the 5 vol% SiC/MoAlB composite.

Fig. 4 (a) Flexural strength and (b) Vickers hardness of SiC/MoAlB composites, together with those of MoAlB for comparison.

Fig. 5 SEM micrographs of crack propagation paths in the 5 vol% SiC/MoAlB composite: (a) a back-scattered electron image of the fractured surface and (b) a second electron image of a crack emanating from the indentation corner.

3.3 Oxidation behavior

Figure 6(a) depicts the oxide scale thickness as a function of time after cyclic oxidation at 1200 and 1300 °C for 10 h in air. The scale thicknesses of SiC/MoAlB are lower than those of MoAlB, i.e., 2.0 vs. 2.7 μm after oxidation at 1200 °C, and 3.9 vs. 5 μm after oxidation at 1300 °C. This result indicates that the scale growth rate on the SiC/MoAlB samples is slower than that on the MoAlB samples. The cross-sectional back-scattered SEM micrographs present the continuous oxide scales after oxidation at 1200 °C (Fig. 6(b)) and 1300 °C (Fig. 6(c)). The formed scales are thin and dense, and mainly composed of Al_2O_3 .

The XRD result demonstrates that Al_2O_3 is the main oxide phase after cyclic oxidation at 1200 °C (Fig. 7(a)). Diffraction peaks with strong intensities belonging to MoAlB are detected, further confirming the thinner scale. No SiC peaks are detected, possibly due to that some SiC are oxidized and the residual SiC with content exceeds the detection limit of XRD. A broaden peak with low intensity locating at the diffraction angle of $\sim 20^\circ$ may be contributed by the amorphous

SiO_2 (Fig. 7(a)). The morphologies of oxides on the composite are illustrated in Figs. 7(b)–7(d). On the oxidized surface, SiO_2 particles are larger, while Al_2O_3 particles are smaller and irregular (Figs. 7(b) and 7(c)). The compositions of the two phases are identified by EDS (Fig. 7(d)). The surfaces of SiO_2 particles are smooth, suggesting the viscous phase formed at above 1200 °C. Small pores formed in the Al_2O_3 scale are irregular, whereas these formed in the SiO_2 particles are round. The appearance of round pores confirms the evaporation of gas phases from the viscous SiO_2 particles upon oxidation at high temperatures. It should be noted that the pores became much round in the SiO_2 particles after oxidation at 1300 °C (Fig. 7(c)). This feature suggests that the higher the temperature, the lower the viscosity of the formed SiO_2 glass phase. The formation of the viscous SiO_2 glass phase at high temperatures is beneficial to sealing the channels for the inward diffusion of O and the outward diffusion of elements from the matrix, contributing to the improvement of oxidation resistance especially at the early stage of oxidation.

Fig. 6 (a) Scale thickness as a function of oxidation time for 5 vol% SiC/MoAlB composite. Cross-sectional back-scattered SEM micrographs of the composite after oxidation at (b) 1200 °C and (c) 1300 °C for 10 h in air.

Fig. 7 (a) XRD pattern of 5 vol% SiC/MoAlB composite after oxidation at 1200 °C for 10 h. SEM micrographs of oxides on the composite after oxidation at (b) 1200 °C and (c) 1300 °C for 10 h in air. (d) EDS mapping for (c).

4 Discussion

Fully dense MoAlB bulk samples are not easy to obtain under hot pressing conditions, possibly due to the existence of small pores caused by the evaporation of MoO_3 or B_2O_3 formed with the absorbed O at sintering temperatures. For example, a relative density of 94% is achieved for the MoAlB samples by hot pressing of MoB and Al powders at 1200 °C with 39 MPa for 5.8 h in vacuum [16]. In the present study, a relative density of about 93% for MoAlB was prepared by hot pressing of a mixture of Mo, Al, and B at 1200 °C with 25 MPa for 1 h in Ar. No full density obtained in the SiC/MoAlB composites should not only be ascribed to the above reason, but also to the absence of sintering reactions between SiC and MoAlB phases. This has been confirmed by the SEM and TEM examinations (Figs. 2 and 3, respectively). The densification of composites without sintering reactions has always been a major challenge. For example, relative densities of 94.4% and 95% are obtained, respectively, in monolithic CrB_2 and 5 wt% $\text{MoSi}_2/\text{CrB}_2$ composite after hot pressing at 1400 °C under 35 MPa for 2 h [28]. To further increase the density of SiC/MoAlB composites, hot isostatic pressing or spark plasma sintering can be considered. It is reasonable to

believe if the density of SiC/MoAlB composites was improved, the properties would be further enhanced.

Upon high temperature oxidation, the following oxidation reactions occur:

For Reaction (1), the sequence of phase formation at temperatures below 1400 °C is $\text{Al}_2\text{O}_3 > \text{B}_2\text{O}_3 > \text{MoO}_3$ [29]. Before a dense and continuous Al_2O_3 scale forms, B_2O_3 and MoO_3 evaporate, thus causing the weight loss upon oxidation at temperatures above 1200 °C [15]. Once the dense and continuous Al_2O_3 scale forms, it acts as a barrier to prevent the inward diffusion of O and the outward diffusion of B and Mo, decreasing the evaporation rate of MoO_3 and B_2O_3 . Therefore, the weight gain is predominant in the MoAlB material during oxidation at high temperatures.

For the oxidation of SiC/MoAlB composites, both Reactions (1) and (2) occur. Reaction (2) induced a fluid glassy phase of SiO_2 at above 1200 °C, similar to the oxidation reaction in a SiC/ $\text{Ti}_3\text{Si(Al)C}_2$ composite [22]. The fluid phase fills some pores and accelerates the formation of dense and continuous oxide scale, decreasing the oxidation rate and leading to the thinner oxide scale on the SiC/MoAlB as compared to the pure MoAlB material.

A cross-sectional back-scattered SEM micrograph presents the microstructure of scale after oxidation at 1300 °C for 10 h in air. It should be noted that the formed SiO_2 is just over a SiC particle (Fig. 8(a)). The two phases are identified by EDS mapping, as shown in Fig. 8(b). This feature suggests that the SiC particles on the surface are gradually *in situ* oxidized to SiO_2 . The small and round pore can be found in the SiO_2 particle, which should be resulted from the evaporation of CO_2 according to Reaction (2) at 1300 °C. It is reasonable to believe that fine SiC particles in the MoAlB will further improve the oxidation resistance of composites due to the fact that the fine reinforcement leads to the rapid formation of SiO_2 which seals microcracks and channels in the Al_2O_3 scale to retard the evaporation of B_2O_3 and MoO_3 in the initial oxidation stage.

Based on the above results, a proposed oxidation resistance mechanism for SiC/MoAlB is presented in Fig. 9. Before the formation of a continuous Al_2O_3 and SiO_2 scale, the evaporation of MoO_3 , B_2O_3 , and CO_2 at

Fig. 8 (a) Cross-sectional back-scattered SEM micrograph and (b) corresponding EDS mapping of 5 vol% SiC/MoAlB composite after oxidation at 1300 °C for 10 h in air.

Fig. 9 Schematic of the oxidation mechanism of SiC/MoAlB as exposed to air.

above 1200 °C induces the weight loss at early oxidation stage. However, the fluid glass of SiO_2 formed at above 1200 °C can seal phase boundaries and fill small pores for retarding the inward diffusion of oxygen. Hence, the oxidation resistance of SiC/MoAlB is better than that of MoAlB even at early oxidation stage. Once the continuous and dense scale forms, the inward diffusion rate of oxygen is retarded, and a low oxygen partial pressure under the scale generates. As a result, the oxidation of Mo and B followed by evaporation of MoO_3 and B_2O_3 is suppressed, leading to weight gain. In addition, the fluid glass of SiO_2 will fill microcracks and small pores in the scale, and further increases the bonding strength between the oxide scale and the matrix. The above analysis explains the reason why SiC/MoAlB has thinner oxide scales than MoAlB after oxidation at 1200 and 1300 °C.

5 Conclusions

5–15 vol% SiC/MoAlB composites were prepared by hot pressing of SiC and MoAlB at 1200 °C under 25 MPa for 1 h in Ar atmosphere. Such hot pressing conditions led to ~92.6% theoretical density in the 5 vol% SiC/MoAlB composite, close to 93% for MoAlB. Increasing SiC content in composites induces the decrease in density. SiC and MoAlB are chemically stable without any reaction products at the sintering temperature of 1200 °C. The 5 vol% SiC/MoAlB composite is stronger and harder than MoAlB. A flexural strength of 380 MPa and a Vickers hardness of 12.7 GPa were achieved in the 5 vol% SiC/MoAlB composite and increased by 24% and 51%, respectively, as compared with those for MoAlB. In addition, the incorporation of SiC also improved the oxidation resistance of MoAlB due to the formation of a dense and continuous scale composed of Al_2O_3 and

SiO₂, which prevents the oxygen inward diffusion and the evaporation of oxides.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 51772020) and Beijing Government Funds for the Constructive Project of Central Universities.

References

- [1] Ade M, Hillebrecht H. Ternary borides Cr₂AlB₂, Cr₃AlB₄ and Cr₄AlB₆: The first members of the series (CrB₂)_nCrAl with $n = 1, 2, 3$ and a unifying concept for ternary borides as MAB-phases. *Inorg Chem* 2015, **54**: 6122–6135.
- [2] Kota S, Sokol M, Barsoum MW. A progress report on the MAB phases: Atomically laminated, ternary transition metal borides. *Int Mater Rev* 2020, **65**: 226–255.
- [3] Bai Y, Qi X, Duff A, *et al.* Density functional theory insights into ternary layered boride MoAlB. *Acta Mater* 2017, **132**: 69–81.
- [4] Lu J, Kota S, Barsoum MW, *et al.* Atomic structure and lattice defects in nanolaminated ternary transition metal borides. *Mater Res Lett* 2017, **5**: 235–241.
- [5] Xiang H, Feng Z, Li Z, *et al.* Theoretical investigations on mechanical and dynamical properties of MAIB (M=Mo,W) nanolaminated borides at ground-states and elevated temperatures. *J Alloys Compd* 2018, **738**: 461–472.
- [6] Kota S, Agne M, Zapata-Solvas E, *et al.* Elastic properties, thermal stability, and thermodynamic parameters of MoAlB. *Phys Rev B* 2017, **95**: 144108.
- [7] Su X, Dong J, Chu L, *et al.* Synthesis, microstructure and properties of MoAlB ceramics prepared by *in situ* reactive spark plasma sintering. *Ceram Int* 2020, **46**: 15214–15221.
- [8] Xu L, Shi O, Liu C, *et al.* Synthesis, microstructure and properties of MoAlB ceramics. *Ceram Int* 2018, **44**: 13396–13401.
- [9] Chen Y, Kota S, Barsoum MW, *et al.* Compressive deformation of MoAlB up to 1100 °C. *J Alloys Compd* 2019, **774**: 1216–1222.
- [10] Zhang H, Kim JY, Su R, *et al.* Defect behavior and radiation tolerance of MAB phases (MoAlB and Fe₂AlB₂) with comparison to MAX phases. *Acta Mater* 2020, **196**: 505–515.
- [11] Bei G, van der Zwaag S, Kota S, *et al.* Ultra-high temperature ablation behavior of MoAlB ceramics under an oxyacetylene flame. *J Eur Ceram Soc* 2019, **39**: 2010–2017.
- [12] Su X, Hu B, Quan Y, *et al.* Ablation behavior and mechanism of bulk MoAlB ceramic at ~1670–2550 °C in air plasma flame. *J Eur Ceram Soc* 2021, **41**: 5474–5483.
- [13] Bai Y, Sun D, Li N, *et al.* High-temperature mechanical properties and thermal shock behavior of ternary-layered MAB phases Fe₂AlB₂. *Int J Refract Met Hard Mater* 2019, **80**: 151–160.
- [14] Zhang H, Xiang H, Dai FZ, *et al.* Oxidation behavior and thermal stability of Cr₂AlB₂ powders. *Corros Sci* 2020, **176**: 108941.
- [15] Mou JJ, Li SB, Yao BX, *et al.* Cyclic oxidation behavior of MoAlB in the temperature range 450–850 °C. *J Alloys Compd* 2020, **831**: 154802.
- [16] Kota S, Zapata-Solvas E, Ly A, *et al.* Synthesis and characterization of an alumina forming nanolaminated boride: MoAlB. *Sci Rep* 2016, **6**: 26475.
- [17] Basu S, Obando N, Gowdy A, *et al.* Long-term oxidation of Ti₂AlC in air and water vapor at 1000–1300 °C temperature range. *J Electrochem Soc* 2012, **159**: C90.
- [18] Li SB, Chen XD, Zhou Y, *et al.* Influence of grain size on high temperature oxidation behavior of Cr₂AlC ceramics. *Ceram Int* 2013, **39**: 2715–2721.
- [19] Yao BX, Li SB, Ma PF, *et al.* Oxidation behavior of MoAl_{0.97}Si_{0.03}B solid solution at 1200–1400 °C. *Mater Today Commun* 2020, **22**: 100846.
- [20] Ma PF, Li SB, Hu J, *et al.* Processing and characterization of MoAl_{1-x}Si_xB solid solutions. *J Alloys Compd* 2020, **814**: 152290.
- [21] Li SB, Xie JX, Zhang LT, *et al.* Mechanical properties and oxidation resistance of Ti₃SiC₂/SiC composite synthesized by *in situ* displacement reaction of Si and TiC. *Mater Lett* 2003, **57**: 3048–3056.
- [22] Li SB, Song GM, Zhou Y. A dense and fine-grained SiC/Ti₃Si(Al)C₂ composite and its high-temperature oxidation behavior. *J Eur Ceram Soc* 2012, **32**: 3435–3444.
- [23] Barsoum MW, Ho-Duc LH, Radovic M, *et al.* Long time oxidation study of Ti₃SiC₂, Ti₃SiC₂/SiC, and Ti₃SiC₂/TiC composites in air. *J Electrochem Soc* 2003, **150**: B166.
- [24] Wan DT, Zhou YC, Hu CF, *et al.* Improved strength-improving contact damage resistance of Ti₃Si(Al)C₂/SiC composites. *J Eur Ceram Soc* 2007, **27**: 2069–2076.
- [25] Zhang J, Wang L, Jiang W, *et al.* High temperature oxidation behavior and mechanism of Ti₃SiC₂–SiC nanocomposites in air. *Compos Sci Technol* 2008, **68**: 1531–1538.
- [26] Zhou X, Jing L, Kwon YD, *et al.* Fabrication of SiC_w/Ti₃SiC₂ composites with improved thermal conductivity and mechanical properties using spark plasma sintering. *J Adv Ceram* 2020, **9**: 462–470.
- [27] Lu XG, Li SB, Zhang WW, *et al.* Thermal shock behavior of a nanolaminated ternary boride: MoAlB. *Ceram Int* 2019, **45**: 9386–9389.

- [28] Reddy V, Sonber JK, Sairam K, *et al.* Densification and mechanical properties of $\text{CrB}_2+\text{MoSi}_2$ based novel composites. *Ceram Int* 2015, **41**: 7611–7617.
- [29] Lu XG, Li SB, Zhang WW, *et al.* Crack healing behavior of a MAB phase: MoAlB . *J Eur Ceram Soc* 2019, **39**: 4023–4028.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original

author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made.

The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.