Crack-healing performance and oxidation behavior of SiC dispersed yttrium silicate composites

Huy Dinh Vu and Makoto Nanko

ABSTRACT
Yttrium silicate-based composites dispersed with silicon carbide particles have been proposed as a novel material concept of self-healing environmental barrier coatings applied for Si-based ceramics and their composites. Crack-healing effectiveness as well as high-temperature oxidation behavior of the yttrium silicate composites was investigated as functions of oxidation time and temperatures. Dense samples of the composites dispersed with 5 vol% SiC particles were fabricated by using the pulsed electric current sintering technique. Thermal oxidation for self-healing was conducted at temperatures ranging from 1000°C to 1300°C for from 1 to 24 h in air. High-temperature oxidation experiments were carried out at temperatures ranging from 1200°C to 1400°C for from 1 to 60 h in air. As a result, the surface cracks with approximately 200 µm in length introduced on the sample surface were disappeared completely after heat treatment at 1300°C for 1 h in air. Crack-healing performance of SiC/Y2SiO3 is better than that of SiC/Y2Si2O7. The crack-healing performance of SiC/Y2SiO3-Y2Si2O7 is in the middle of that of SiC/Y2SiO3 and SiC/Y2Si2O7. The mechanism of crack healing was identified as the consequence of SiO oxidation into SiO2, which accompanies a volume expansion, and outward diffusion of Y3+ cations caused the formation of Y2Si2O7 outer layer. Oxidation of SiC particles within the matrix developed an oxidized zone. Growth of the oxidized zone obeyed the parabolic law, which meant diffusion process in the oxidized zone is the rate-controlling process.

1. Introduction
Silicon-based ceramics, including silicon nitride and silicon carbide as well as their ceramic matrix composites, such as SiC fiber-reinforced SiC composites (SiC/SiC), are used as structural components for hot section in gas turbine engines. These materials present an excellent high-temperature oxidation resistance under dry and clean air due to the growth of a protective silica layer [1]. However, in water vapor generated during combustion process in gas turbine engines, these ceramics were susceptible to hot corrosion and recession. The protective silica layer reacts with water vapor to form gaseous oxidation products such as Si(OH)4 [2]. In order to extend lifetime of these materials, the application of environmental barrier coatings (EBCs) to protect them from water vapor corrosion is needed.

EBCs must fulfill several requirements to achieve their purpose as protective coatings, such as chemical compatibility with the substrate, phase stability, and a low coefficient of thermal expansion (CTE) close to that of the substrate. Design of EBCs usually consists of two or more coating layers. Among the constituents of EBCs for the SiC/SiC composites are barium-strontium-aluminosilicate, hafnia/zirconia-based system, and rare-earth mono- and di-silicate [3–5]. Recent studies on EBCs showed that rare-earth silicates (RE2SiO3 and RE2Si2O7) are potential materials for the EBCs due to their phase stability and low CTE close to those of silicon-based ceramic substrates. However, cracking of the rare-earth silicates was detected [4]. In actual applications, further cracking can be induced by foreign object damage, mechanical fatigue or thermal shock. In case of crack formation in the EBCs, the substrates will be no longer protected from the corrosive environment due to penetration of oxygen and water vapor. Under these circumstances, crack-healing abilities are essentially necessary for the EBCs to increase their lifetime and reliability.

The authors have proposed SiC/Y2SiO3 composites as the self-healing EBCs material applied for SiC/SiC composites substrate [6]. Y2SiO3 composites dispersed with 5 vol% SiC particles exhibited a good crack-healing ability induced by high-temperature oxidation process. The surface cracks with approximately 200 µm in length were disappeared completely after heat treatment at 1300°C for 1 h in air. The surface cracks were filled up by the oxidation product of Y2Si2O7, which was formed via outward diffusion of Y3+ cations. Self-healing of surface cracks caused bending strength recovery of SiC/Y2Si2O3 composites. Crack-healing function of SiC/Y2Si2O3 composites could be an excellent approach to protect SiC/SiC composites substrate from water vapor corrosion when the substrate is...
exposed to atmosphere due to coating damage. However, the key limitation in the applicability of the EBCs for SiC/SiC composites is the CTE mismatch between the coating and the substrate. In order to reduce the CTE mismatch, CTE of the selected coating needs to be closest to that of the substrate. While \( Y_2 \) \( \text{SiO}_3 \) has large CTE mismatch with SiC whereas \( Y_2\text{Si}_2\text{O}_7 \) possesses a good match to SiC [7,8]. A comparison between CTE of SiC (4.3–5.4 × 10\(^{-6}\) K\(^{-1}\)) and that of \( Y_2 \) \( \text{SiO}_3 \) (7.8 × 10\(^{-6}\) K\(^{-1}\)) and \( Y_2\text{Si}_2\text{O}_7 \) (3.9 × 10\(^{-6}\) K\(^{-1}\)) also indicates that the CTE value of SiC is in middle of that of \( Y_2 \) \( \text{SiO}_3 \) and \( Y_2\text{Si}_2\text{O}_7 \). This fact shows that \( Y_2\text{SiO}_3 \) and \( Y_2\text{Si}_2\text{O}_7 \) ceramics can be mixed together to fabricate a ceramic displaying the CTE closest to that of the substrate. From these findings, \( Y_2\text{Si}_2\text{O}_7 \) and \( Y_2\text{SiO}_3-Y_2\text{Si}_2\text{O}_7 \) composites dispersed with SiC particle will be potential self-healing EBC materials of SiC/\( \gamma \)-\( \text{SiO}_2 \) composites. Crack-healing performances of these composites should be evaluated and compared to each other.

Nguyen et al. [9,10] have reported on the crack-healing ability of \( \text{Yb}_2\text{SiO}_5-Y\gamma\text{Si}_2\text{O}_7 \) composites dispersed with SiC particles. With 10 vol% SiC dispersoids, cracks on the sample surface of SiC/\( \text{Yb}_2\text{SiO}_5-Y\gamma\text{Si}_2\text{O}_7 \) composites were healed completely after heat treatment at 1250°C in air. The closure of surface cracks was identified as a consequence of a volume expansion of newly formed \( \text{Yb}_2\text{Si}_2\text{O}_7 \) phase. However, the formation of new \( \text{Yb}_2\text{Si}_2\text{O}_7 \) phase on surface of cracks was not discussed kinetically. Taking account of self-healing mechanism, Kim et al. [11] have reported on crack-healing behavior of liquid-phase sintered silicon carbide ceramics. Cracks were healed due to oxidation of crack surfaces. The diffusion of oxygen and other ions along intergranular phases to the crack surfaces resulted in the formation of oxidation products. The oxidation products filled in the cracks and caused closure of the cracks. From the above previous studies, the formation of oxidation products on crack surfaces which are responsible for crack-healing should be considered as the consequence of the diffusion of ions.

Furthermore, the self-healing composites were toughened by a non-oxide phase [6]. Crack-healing ability of the composites was induced by oxidation of the non-oxide dispersoid. The oxidation of the dispersoid could affect the properties of the composites. In order to apply these composites at high temperatures, oxidation resistance of these materials must be studied.

In this study, self-healing function was investigated on 5 vol% SiC dispersed yttrium silicate composites, including SiC/\( Y_2\text{SiO}_3 \), SiC/\( Y_2\text{Si}_2\text{O}_7 \), and SiC/\( Y_2\text{Si}_2\text{O}_7-Y_2\text{Si}_2\text{O}_7 \), as functions of heat treatment temperatures and time. High-temperature oxidation was carried out to estimate and clarify the oxidation resistance and the self-healing mechanism of these composites. Crack-healing mechanism of the composites was discussed and schematically illustrated.

2. Experimental procedure

2.1. Synthesis of yttrium silicate powder (\( Y_2\text{Si}_2\text{O}_7 \) and \( Y_2\text{SiO}_3 \) ceramics)

The single-phase \( \gamma-Y_2\text{Si}_2\text{O}_7 \) powder was fabricated by solid-state reaction method from powder mixture containing \( Y_2\text{O}_3 \) (Nippon Yttrium Co., Ltd, 99.9% purity, \( d = 1.1 \) µm) and SiO\(_2\) powder (Nacalai Tesque, Inc., 99% purity). The mixture in a molar ratio 1:2 consisting of \( Y_2\text{O}_3 \) and SiO\(_2\) powder was ball-milled in a plastic bottle with ethanol and alumina balls for 24 h. After drying and manual crashing, the mixture was annealed at 1500°C for 24 h in air. The received powder was phase-identified by using X-ray diffraction (XRD). Figure 1 shows XRD pattern of the powder fabricated by the above procedure. Only single-phase \( \gamma-Y_2\text{Si}_2\text{O}_7 \) is detected and it corresponds to standard pattern of \( \gamma-Y_2\text{Si}_2\text{O}_7 \) (ICDD Card No. 42-0167).

The synthesis procedure of single-phase \( Y_2\text{SiO}_3 \) was mentioned previously [12].

2.2. Preparation of SiC/\( Y_2\text{SiO}_3 \), SiC/\( Y_2\text{Si}_2\text{O}_7 \) and SiC/\( Y_2\text{Si}_2\text{O}_7-Y_2\text{Si}_2\text{O}_7 \) bulk samples

Sample preparation of \( Y_2\text{SiO}_3 \), \( Y_2\text{Si}_2\text{O}_7 \) and \( Y_2\text{SiO}_3-Y_2\text{Si}_2\text{O}_7 \) (mixing in a volume ratio of 3:7) composites dispersed with SiC particles was carried out as the following procedure. A slurry mixture containing 5 vol% SiC (Ibiden Co., Ltd, 99.9% impurity, 0.32 µm mean particle size), ceramic matrices powder and ethanol was prepared by ball-milling for 24 h in a plastic bottle with alumina balls. The slurry was dried at 100°C for 10 h in air and milled manually by using an alumina mortar to eliminate the agglomeration of the particles. Consolidation of the powder mixtures was carried out by pulsed electric current sintering with a graphite die in vacuum for 5 min holding time and under 70 MPa in uniaxial pressure at 1600°C for \( Y_2\text{SiO}_3 \), 1500°C for \( Y_2\text{Si}_2\text{O}_7 \) and 1550°C for \( Y_2\text{SiO}_3-Y_2\text{Si}_2\text{O}_7 \) matrix composites. The relative density of all as-sintered
specimens was reached at least 99% of the theoretical one. Figure 2 shows scanning electron microscope (SEM) image representative for the fracture surface of the as-sintered samples. SiC particles are visible as the bright dots dispersed homogeneously into the matrices. The bulk samples were then cut and ground by a grinding wheel with diamond grains of 30 µm and polished with diamond particles slurry (2 µm).

2.3. Crack-healing and high-temperature oxidation test

In order to investigate the crack-disappearance performance of these composites, three indentations and derived cracks were introduced on a polished surface of each sample by using a Vickers hardness indenter at a load of 20 N for 10 s. Surface cracks of 180–200 µm in length were made by this method, as shown in Figure 3. After pre-cracking, the specimens were annealed at temperatures ranging from 1000°C to 1300°C for 1–24 h in air. Surface cracks before and after heat treatment were observed by using SEM. Fraction of surface crack disappearance was evaluated by the measurement length of the cracks before and after heat treatment as Maruoka et al. [13] mentioned previously. The heat-treated samples were also analyzed by XRD for phase identification.

High-temperature oxidation tests at temperatures ranging from 1200°C to 1400°C for 1 to 60 h of these composites were conducted as the following steps. The specimens were put on zirconia balls (2 mm in diameter) in an alumina crucible and oxidized at the targeted temperatures in air. The heating rate in the...
oxidation experiments was 400°C/h. Then, oxidized samples were cross-sectioned and polished with a slurry of diamond particles (2 µm). The microstructure of the cross-section was observed by SEM to determine the thickness of oxidized zone. The phase identification of oxidized samples was carried out by using XRD.

3. Results

3.1. Crack-disappearance performance of the composites

Figure 4 shows SEM images of surface cracks after heat treatment at 1300°C for 1 h in air. Before heat treatment, surface cracks, indicated by white arrows, can be obviously observed in Figure 3. The surface cracks were initially disappeared at the crack tips and then the disappeared area extended to the corner of the indentation by heat treatment. Surface cracks were completely disappeared after heat treatment at 1300°C for 1 h in air.

The XRD patterns of SiC/Y2SiO5, SiC/Y2Si2O7 and SiC/Y2SiO5-Y2Si2O7 composites are presented in Figure 5. Figure 5(a) shows the results of SiC/Y2SiO5 composites. A new phase, identified to be Y2Si2O7, can be detected. The oxidation process could occur as equations (1) and (2). The XRD results of SiC/Y2Si2O7 composites are shown in Figure 5(b). A comparison of these results indicates that no new peaks were detected. However, the intensity of SiC peak was decreased. This fact indicates that SiC was oxidized into SiO2 as an amorphous phase, following equations (3) and (4). It could not be detected. Figure 5(c) reveals the XRD results of SiC/Y2SiO5-Y2Si2O7 composites. No new peaks were detected. Oxidation reactions that occurred in the annealing process are similar to that of SiC/Y2SiO5 composites. Oxidation of SiC into amorphous SiO2 could occur as well.

\[ \text{Y}_2\text{SiO}_5 + \text{SiC} + 2\text{O}_2 = \text{Y}_2\text{Si}_2\text{O}_7 + \text{CO}_2 \]  
\[ \text{Y}_2\text{SiO}_5 + \text{SiC} + 3/2\text{O}_2 = \text{Y}_2\text{Si}_2\text{O}_7 + \text{CO} \]  
\[ \text{SiC} + 2\text{O}_2 = \text{SiO}_2 + \text{CO}_2 \]  
\[ \text{SiC} + 3/2\text{O}_2 = \text{SiO}_2 + \text{CO} \]

Figure 5 shows the graph of crack disappearance of the composites as functions of heat treatment time and temperatures. The crack disappearance was classified by three groups including less, partial, and complete disappearance. The results show that the crack-healing effectiveness is increased by increasing the healing time and temperatures.

Figure 4. SEM images of surface cracks after heat treatment at 1300°C for 1 h in air: (a) SiC/Y2SiO5, (b) SiC/Y2Si2O7 and (c) SiC/Y2SiO5-Y2Si2O7.
and mixed matrix composites, is better than that of SiC/Y<sub>k</sub> composites. Composites show crack-healing of cations, which was responsible for the formation of SiC/Y<sub>k</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>. The thickness of the oxidized zone was increased with the increase in oxidation time as well as oxidation temperatures. The growth of oxidized zone seemed to obey the parabolic law:

\[ x^2 = k_p t \]  

where \( k_p \) is the parabolic rate constant. As the oxidized zone is almost dense, as shown in Figure 7, mass transport in the oxidized zone is the predominant process for growth of the oxidized zone. The oxidation results of SiC/Y<sub>k</sub>SiO<sub>2</sub> composites, as shown in Figure 8, revealed that the oxidation rate at 1200°C is larger than that at 1300°C and 1400°C. This behavior depends on difference in the diffusion rates of oxygen through the matrix and the reaction product. This phenomenon is further discussed in the next section.

### 4. Discussion

The crack-disappearance results of SiC/Y<sub>k</sub>SiO<sub>2</sub>, SiC/Y<sub>k</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>, and SiC/Y<sub>k</sub>SiO<sub>2</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> composites, shown in Figure 6, indicated that crack-healing performance of SiC/Y<sub>k</sub>SiO<sub>2</sub> is better than that of SiC/Y<sub>k</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> and SiC/Y<sub>k</sub>SiO<sub>2</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>. SiC/Y<sub>k</sub>SiO<sub>2</sub> composites show crack-healing effectiveness comparable with SiC/Y<sub>k</sub>SiO<sub>2</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> one. In order to clearly understand the difference in crack-healing performance of Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> and mixed matrix composites, a comparison in crack disappearance of these composites is revealed in Figure 11. The crack-healing effectiveness of SiC/Y<sub>k</sub>SiO<sub>2</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> is in the middle of that of SiC/Y<sub>k</sub>SiO<sub>2</sub> and SiC/Y<sub>k</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>. In order to clarify the difference in crack-healing performance of those composite, the crack-healing mechanism of SiC/Y<sub>k</sub>SiO<sub>2</sub> and SiC/Y<sub>k</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> are discussed based on the high-temperature oxidation behavior of these composites.

As the previous report [6], the outward diffusion of Y<sup>3+</sup> cations, which was responsible for the formation of Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> layer on the sample surface, plays a major role in the crack-healing effectiveness of SiC/Y<sub>k</sub>SiO<sub>2</sub> composites. The formation of sub-micron spherical voids after high-temperature oxidation is the evidence of the outward diffusion of cations, as shown in Figure 7(a). Although the outward diffusion of cations could cause the formation of oxidation product layer on the sample surface, the oxidation product layer is not obviously observed on the surface of SiC/Y<sub>k</sub>SiO<sub>2</sub>. This suggests that the contribution of outward diffusion of cations in

![Figure 5. XRD results of (a) SiC/Y<sub>k</sub>SiO<sub>2</sub>, (b) SiC/Y<sub>k</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>, and (c) SiC/Y<sub>k</sub>SiO<sub>2</sub>-Y<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> composites.](image-url)
Figure 6. Crack-disappearance performance of (a) SiC/Y₂SiO₅, (b) SiC/Y₂Si₂O₇ and (c) SiC/Y₂SiO₅–Y₂Si₂O₇ composites.

Figure 7. Cross-sectional views of oxidized zone in (a) SiC/Y₂SiO₅, (b) SiC/Y₂Si₂O₇ and (c) SiC/Y₂SiO₅–Y₂Si₂O₇ after exposed at 1300°C for 24 h in air.
this ceramic composite may be not so strong for high-temperature oxidation. This assumption can be also explained through the formation of short cracks after annealing, as shown in Figure 7(a). Inward diffusion of oxygen passing through Y₂SiO₅ matrix gives a volume expansion of SiC dispersion upon conversion to Y₂Si₂O₇. The volume expansion of the SiC dispersion causes the formation of the short cracks. If the outward diffusion of cations is much faster than inward diffusion of oxygen, the volume expansion would be completely compensated due to the formation of the voids in the interior of the sample. It means that volume change in the inside of the oxidized zone will be negative. And, the interior cracks will not be appeared. This behavior was observed in Ni/Al₂O₃ and Ni/MgO composites after high-temperature oxidation [14]. In the case of SiC/Y₂SiO₅, the contribution of cation diffusion is not yet able to obtain quantitatively. The rate of cation diffusion is equal to or a little lower than that of oxygen diffusion.

However, in the case of SiC/Y₂Si₂O₇ composites, a lot of short cracks parallel to the sample surface are generated in the inside of the oxidized zone, as shown in Figure 7(b). Similar cracks were observed in Y₂O₃ partially stabilized ZrO₂ composites dispersed with Ni particles after the oxidation process at high temperatures [15]. The cracks appeared in the inside of the oxidized zone of SiC/Y₂Si₂O₇ composites would be formed by oxidation of SiC dispersoid into SiO₂ which accompanies a volume expansion during high-temperature oxidation process. Theoretical value of the volume expansion of oxidation of SiC into SiO₂ is approximately equal to be two. This volume expansion caused the closure of surface cracks. Besides, the healing of surface cracks can be caused by the formation of amorphous SiO₂. The SiC dispersoid was oxidized into amorphous SiO₂. The amorphous SiO₂ subsequently migrated along surface cracks leading to full filling of the cracks. The same mechanism was observed in yttria-stabilized zirconia composites dispersed with MoSi₂ [16]. Moreover, as shown in Figure 7(b), some spherical voids can be observed in the oxidized zone as well. The formation of these voids was caused by outward diffusion of Y³⁺ cations. A comparison between the cracks and voids appeared in the inside of the oxidized zone indicates that the volume change in the oxidized zone will be positive. It means that the outward diffusion of cations in the Y₂Si₂O₇ matrix is much slower than

![Figure 8](image1.png)  ![Figure 9](image2.png)

**Figure 8.** Thickness of oxidized zone as a function of oxidation time at various oxidation temperatures for SiC/Y₂SiO₅ composites: (a) time dependence of the thickness of oxidized zone and (b) parabolic plot on growth of oxidized zone.

**Figure 9.** Thickness of oxidized zone as a function of oxidation time at various oxidation temperatures for SiC/Y₂Si₂O₇ composites: (a) time dependence of the thickness of oxidized zone and (b) parabolic plot on growth of oxidized zone.
the inward diffusion of oxygen. Because the outward diffusion of cations is so slow, it displays the minor role in crack-healing performance of SiC/Y2Si2O7 composites. The dominant factor causes the self-healing of SiC/Y2Si2O7 would be the volume expansion, which was accompanied by oxidation of SiC dispersoid into amorphous SiO2 phase.

Taking account of the above discussion, the crack-healing mechanism of SiC/Y2SiO5-Y2Si2O7 composites is illustrated in Figure 12. The surface cracks are filled in by the oxidation product, which was formed by the
outward diffusion of cations and closed by the volume expansion accompanied by oxidation of the SiC dispersion.

As mentioned in Section 3, in the case of SiC/Y2SiO5 composites, the oxidation rate of the composites at 1200°C is larger than that at 1300°C and 1400°C. This phenomenon is caused by the difference in oxidation mode of the composites at various temperatures. Schematic representations of oxidation mode on SiC/Y2SiO5 composites at various temperatures are revealed in Figure 13. The oxidation modes for SiC-reinforced ceramic matrix composite materials have been proposed by Luthra et al. [17]. At high temperatures, oxygen can penetrate into Y2SiO5 matrix and causes the oxidation reaction of SiC particles and Y2SiO5 matrix. This process results in the formation of oxidation product Y2Si2O7 and development of the oxidized zone. All SiC particles in the oxidized zone were partially oxidized and developed a finite thickness of the oxidation product, as shown in Figure 13(a). In the case of the oxidation process at 1300°C and 1400°C, the oxygen diffusion rate through Y2SiO5 matrix is much larger than that through the oxidation product. Almost SiC particles in the oxidized zone were fully oxidized. The interface between the oxidized and the non-oxidized zone is not sharp. There would be an area of the oxidized zone containing partially oxidized SiC particle, as shown in Figure 13(b). The results on growth rate constant of the oxidized zone of SiC/Y2Si2O7 and SiC/Y2SiO5-Y2Si2O7 composites suggest that their oxidation modes are similar to that of SiC/Y2SiO5 composites at 1300°C and 1400°C.

Figure 14 plots the parabolic rate constant, k, as a function of reciprocal oxidation temperatures. These plots will form straight lines. The apparent activation energy for the oxidation reaction can be determined by finding the slope of the line. As the above discussion, the oxidation mode of SiC/Y2SiO5 composites at 1200°C is not similar to that at 1300°C and 1400°C, as well as the oxidation mode of SiC/Y2Si2O7 and SiC/Y2SiO5-Y2Si2O7 composites. Therefore, the straight line of SiC/Y2SiO5 is formed with a data point of k value at 1300°C and 1400°C. Taking account of the circumstances, the apparent activation energies on the growth of oxidized zone in SiC/Y2SiO5, SiC/Y2Si2O7, and SiC/Y2SiO5-Y2Si2O7 were calculated to be 332, 735 and 383 kJ mol⁻¹, respectively. These results indicate that the oxidation rate of SiC/Y2Si2O7 is lower in magnitude than that of SiC/Y2SiO5 and SiC/Y2SiO5-Y2Si2O7, in particular, at low temperatures. In the case of SiC/Y2SiO5-Y2Si2O7 composites, although Y2SiO5 is just possessed 30% volume of the mixed matrix, difference in the activation energy of mixed matrix and Y2SiO5 matrix composites is not much. This indicates that inward diffusion of oxide ions through Y2SiO5 ceramic is the major contribution to develop the oxidized zone of SiC/Y2SiO5-Y2Si2O7 composites.

5. Conclusion

Crack-healing function and high-temperature oxidation behavior of SiC/Y2SiO5, SiC/Y2Si2O7, and SiC/Y2SiO5-Y2Si2O7 composites, which will be applied for EBCs of SiC/SiC composites substrate, were investigated as

Figure 13. Schematic illustration of oxidation mode on SiC/Y2SiO5 composites at (a) 1200°C and (b) 1300°C and 1400°C.
functions of oxidation time and temperatures in air. These composites possess a considerable crack-healing ability induced by high-temperature oxidation. The surface cracks were perfectly healed after annealing at 1300°C for 1 h in air. The formation of oxidation product layer and the volume expansion is responsible for closure of the surface cracks. The formation of the outer layer was considered as the outward diffusion of $\text{Y}^{3+}$ cations. The oxidation of SiC dispersoid into $\text{SiO}_2$ caused the volume expansion. The oxidation of SiC particles within the yttrium silicate matrices at high temperature induced the formation of an internal oxidation zone. Growth of the oxidized zone obeyed the parabolic law, which indicated that the mass transport in the oxidized zone was the rate-controlling process. The oxidation and crack-disappearance rate of $\text{SiC}/\text{Y}_2\text{SiO}_5-\text{Y}_2\text{Si}_2\text{O}_7$ composites has middle values between the values of $\text{SiC}/\text{Y}_2\text{SiO}_5$ and $\text{SiC}/\text{Y}_2\text{Si}_2\text{O}_7$ one.

**Acknowledgments**

The authors wish to express their gratitude to the Japan Science and Technology Agency for supporting partially this study through the Advanced Low Carbon Technology Research and Development Program.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**References**

[1] Min JB, Harris DL, Ting JM. Advances in ceramic matrix composite blade damping characteristics for aerospace turbomachinery applications. Proceeding of S2nd Structures, Structural Dynamics and Materials Conference; 2011 April 04–07; Colorado, US: Denver.
[2] Jacobson NS. Corrosion of silicon-based ceramics in combustion environments. J Am Ceram Soc. 1993;76(1):3–28.
[3] Lee KN, Fox DS, Robinson RC, et al. Environmental barrier coatings for silicon-based ceramics. In: Krenkel W, Naslain R, Schneider H, editors. High temperature ceramic matrix composites. Weinheim (Germany): Wiley-VCH; 2001. p. 224–229.
[4] Lee KN, Fox DS, Bansal NP. Rare earth silicate environmental barrier coatings for SiC/SiC composites and $\text{Si}_3\text{N}_4$ ceramics. J Euro Ceram Soc. 2005;25(10):1705–1715.
[5] Zhu DM, Miller RA, Fox DS. Thermal and environmental barrier coating development for advanced propulsion engine systems. Ohio (US): NASA Glenn research center; 2008.
[6] Vu HD, Nanko M. Crack-healing behavior and mechanical strength recovery of 5 vol% silicon carbide particles dispersed yttrium monosilicate composites. Mater Trans. 2019;60(1):149–155.
[7] Dolan MB, Harlan B, White JS, et al. Structures and anisotropic thermal expansion of the $\alpha$, $\beta$, $\gamma$ and $\delta$ polymorph of $\text{Y}_2\text{Si}_2\text{O}_7$. Powder Diff. 2008;23(1):20–25.
[8] Fukuda K, Matsubara H. Anisotropic thermal expansion in yttrium silicate. J Mater Res. 2003;18(7):1715–1722.
[9] Nguyen ST, Nakayama T, Suematsu H, et al. Strength improve and purification of $\text{Yb}_2\text{Si}_2\text{O}_7$-SiC nanocomposites by surface oxidation treatment. J Am Ceram Soc. 2017;100(7):3122–3131.
[10] Nguyen ST, Nakayama T, Suematsu H, et al. Self-crack healing ability and strength recovery in ytterbium disilicate/silicon carbide nanocomposites. J App Ceram Tech. 2019;16(1):39–49.
[11] Kim YW, Ando K, Chu MC. Crack healing behavior of liquid-phase-sintered silicon carbide ceramics. J Am Ceram Soc. 2003;86(3):465–470.
[12] Vu HD, Nanko M. Self-healing behavior of $\text{Y}_2\text{SiO}_3$ toughened by SiC particles. Key Eng Mater. 2017;728:149–155.
[13] Maruoka D, Nanko M. Crack-healing of nano-Ni/Al$_2$O$_3$ hybrid materials via high-temperature oxidation. Mater Sci Forum. 2011;696:378–383.
[14] Nanko M, Matsumaru K, Ishizaki K. Role of cation diffusion on high temperature oxidation of metal dispersed ceramic matrix composites. Adv Technol Mater Mater Proc J. 2005;7(1):5–8.

[15] Nanko M, Yoshimura M, Maruyama T. High temperature oxidation of \(Y_2O_3\) partially-stabilized \(ZrO_2\) composites dispersed with Ni particles. Mater Trans. 2003;44(4):736–742.

[16] Sloof WG, Turteltaub SR, Carabat AL, et al. Crack healing in yttria stabilized zirconia thermal barrier coatings. In: Zwaag VD, Brinkman E, editors. Self-healing materials. Amsterdam (Netherlands): IOS Press; 2015. p. 219–227.

[17] Luthra KL, Park HD. Oxidation of silicon carbide-reinforced oxide-matrix composites at 1375 to 1575°C. C. J Am Ceram Soc. 1990;73(4):1014–1023.