Research article

Water vapor and CMAS corrosion tests of Y$_2$SiO$_5$/Si thermal and environmental barrier coating

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ABSTRACT

Thermal and environmental barrier coatings (TEBCs), an up-to-date concept, are introduced to protect silicon-based ceramic matrix composites (CMCs) from not only high-temperature water vapor but also alkali salts from volcanic ash and dust suspended in the atmosphere. Both high-temperature steam and CMAS will cause Si-based CMCs to deteriorate rapidly. By executing the corrosion test against high-temperature water vapor, we find that the Y$_2$SiO$_5$/Si double-layer TEBC can effectively protect SiCf/SiC CMCs from water vapor at 1300 °C for over 205 h. Almost all Y$_2$SiO$_5$ transforms into Y$_{4.67}$(SiO$_4$)$_3$O after the corrosion test. It is also found that in the CMAS corrosion test, the reaction zone formed between the CMAS and Y$_2$SiO$_5$ layers prevents the mutual diffusion of elements in the CMAS and Y$_2$SiO$_5$ layers. The apparent activation energy of the reaction between CMAS and Y$_2$SiO$_5$ in the 1200–1300 °C temperature range is calculated to be 713.749 kJ/mol. These findings provide a reference for selecting appropriate materials for TEBCs.

1. Introduction

To further develop a high thrust-weight ratio aero engine, simultaneously decreasing the weight of the hot section structural components and improving the inlet temperature of the combustion room is the most efficient approach [1]. A nickel-based high-temperature alloy is used as the hot section structural material in the aero engine. However, the operating temperature in the combustion room is already out of the usage temperature limit of the Ni-based alloy, which restricts the further improvement of the thrust-weight ratio. Si-based ceramic matrix composites (CMCs), such as carbon fiber-reinforced silicon carbide CMC (Cf/SiC CMC) and silicon carbide fiber-reinforced silicon carbide CMC (SiCf/SiC CMC), are promising candidates for hot section structural components due to their low density, exceptional thermomechanical stability and good oxidation resistance [2, 3, 4]. In dry air, Si-based CMCs will react with oxygen to form silica, which can isolate oxygen and prevent Si-based CMCs from being oxidized further. However, the operating environment of Si-based CMCs is full of hot gas containing high-temperature water vapor. Passive silica will react with water vapor to form volatile Si(OH)$_4$ [5]. The volatile Si(OH)$_4$ can be easily brushed away by high-pressure hot gas, continuously exposing the Si-based CMC to hot gas. Continuous corrosion from water vapor causes Si-based CMCs to deteriorate rapidly.

The environmental barrier coating (EBC) fabricated on the surface of the Si-based CMC aims to protect the Si-based CMC from hot gas. The EBC is always made up of two or three layers of coatings containing the top layer and bond layer. The materials used as the top layer of the EBC should satisfy some requirements. For example, excellent water vapor corrosion resistance is the most fundamental requirement. The coefficient of thermal expansion (CTE) of materials should be as close to the CTE of the Si-based CMC as possible to avoid cracking and delamination of the coating. In addition, materials must be stable and compatible with the bond layer so that deleterious reactions will not occur. The bond coating is deposited to alleviate the thermal mismatch between the top layer and Si-based CMC resulting from the widely varying CTE between them. When oxygen permeates into the coating along the cracks in the top layer, the bond layer will consume oxygen and stop them from continuously diffusing inward [6]. Over the past thirty years, research on EBCs has made great breakthroughs. It has been proven that EBCs effectively extend the service time of Si-based CMCs [7]. The up-to-date EBC system containing a rare earth silicate top layer and silicon bond layer has been proven to be the best candidate.
Studies have shown that the resistance of monosilicates to high-temperature water vapor is much better than that of rare earth disilicates [6]. In addition, there are at most seven types of crystal structures of one disilicate over a wide temperature range [8,9]. The CTE of different crystal structures varies greatly, which has an adverse influence on the integrality of the EBC. There are only two types of crystal structures for every monosilicate [8,9]. Therefore, monosilicate is much more suitable for use as the top layer of the EBC. Y<sub>2</sub>SiO<sub>5</sub> is the best candidate among the many rare earth monosilicates due to its superior thermal and mechanical properties under high-temperature conditions [10, 11, 12, 13, 14, 15, 16, 17]. The water vapor corrosion resistance of Y<sub>2</sub>SiO<sub>5</sub> is also proven to be better than those of other monosilicates from both experiments and simulated calculations [13, 14, 15]. However, few studies have been conducted on the resistance to water vapor corrosion of TEBCs with Si interlayers. The role of the Si layer in the entire etching process is not clear, and it needs to be studied.

The damage to Si-based CMCs caused by high-temperature water vapor can be alleviated through EBCs, as illustrated by several studies [14,18,19]. However, Si-based CMCs still face the risk of being corroded from the local alkali salts. Foreign alkali salts will react with each other at high temperature to form the CMAS glass. CMAS can slowly permeate into the SiO<sub>2</sub> thin layer on the surface of the Si-based CMC, destroying the protection of SiO<sub>2</sub> for the Si-based CMC. The Si-based CMC itself can be operated at extremely high temperatures, and thus, in addition to high-temperature water vapor, the EBC only needs to protect the Si-based CMC against CMAS, similar to the role of the TBC in Ni-based alloys. Thermal and environmental barrier coatings (TEBCs) are urgently needed [20]. However, most studies only focus on the water vapor corrosion resistance of rare earth silicates. For CMAS corrosion, most of the research focuses on its reaction products, and there are few studies on the reaction parameters, such as the reaction rate and activation energy. Hence, the reaction parameters will also be investigated in this paper to more comprehensively evaluate the CMAS resistance of coatings.

We deposited the Y<sub>2</sub>SiO<sub>5</sub>/Si double-layer TEBC on a SiCf/SiC substrate by air plasma spraying (APS). The high-temperature resistance against water vapor and CMAS of Y<sub>2</sub>SiO<sub>5</sub>/Si TEBCs were investigated. The corrosion behaviors and mechanisms were also discussed in detail.

2. Materials and methods

2.1. Deposition of coatings

The Y<sub>2</sub>SiO<sub>5</sub>/Si coating was deposited over the top of SiCf/SiC composite substrates covered with silicon coating by an air plasma spraying instrument (GTS-5500, Praxair, America) equipped with an SG-100 spraying gun. The substrate used in the experiment was provided by the Research Center of Composite Materials with a size of 17 mm × 15 mm × 3 mm. It is noticeable that when we purchased the substrates, a silicon coating with a thickness of 80 μm had already been fabricated on the surface of the SiCf/SiC composite substrates.

The Y<sub>2</sub>SiO<sub>5</sub> powders used for top deposition were obtained by spray granulating and calcining with purchased Y<sub>2</sub>SiO<sub>5</sub> powders (>99.9%, 1–3 μm, Beijing Zhongqinian New Material Technology Co., Ltd., Beijing, China). The slurry used in spray granulation was a mixture of Y<sub>2</sub>SiO<sub>5</sub> powders (35 wt.%), polyvinyl alcohol (PVA, 0.5 wt.%), and deionized water. After spray granulation, the Y<sub>2</sub>SiO<sub>5</sub> powders were calcined at 1100 °C in a furnace to remove PVA and achieve densification. The densified Y<sub>2</sub>SiO<sub>5</sub> powders were sieved to obtain the spraying powders meeting the flowability requirement in the APS process.

The Y<sub>2</sub>SiO<sub>5</sub> powders were then ultrasonically cleaned in ethanol for 30 min to release the stress generated in the preparation process. The Y<sub>2</sub>SiO<sub>5</sub>/Si-coated substrates were then ultrasonically cleaned in ethanol for further testing.

2.2. Water vapor corrosion test

Water vapor corrosion tests of Y<sub>2</sub>SiO<sub>5</sub>/Si-coated SiCf/SiC substrates at elevated temperatures were carried out in a tube furnace (GSL-1600X, Hefei Kejing Material Technology Co., Ltd.). The test was performed at 1300 °C in a 90% H<sub>2</sub>O/10% O<sub>2</sub> atmosphere with a 10-hour rotation. The gas generator (LVD-F1, Hefei Kejing Material Technology Co., Ltd.) was used to generate the vapor, and the flow rate of steam was 0.17 cm/s. To accurately obtain the weight change tendency of the samples during the water vapor corrosion process, the samples on the alumina boat were removed from the tube furnace, and the weight was measured by a high-precision electronic scale (the accuracy reached 0.0001 g) every 10 h.

2.3. CMAS corrosion test

The 38CaO–5MgO–8Al<sub>2</sub>O<sub>3</sub>–49SiO<sub>2</sub> (CMAS) was used as a corrosive medium to simulate the practical situation of aero-energy in service. The CMAS powders were ground and uniformly coated on the surface of the coating and then heated to 1200, 1250 and 1300 °C in a furnace at a heating rate of 5 °C/min for 15, 90, 150 and 240 min. The amount of CMAS applied was 0.05 g/cm². The changes in the thickness of the corrosion layer with time were jointly determined by SEM and EDS, which were measured multiple times and averaged. The CMAS powders used in this work were synthesized at 1550 °C for 4 h with CaO, MgO, Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> in a molar ratio of 38:5:4:49. The CaO and Al<sub>2</sub>O<sub>3</sub> powders (AR, 3–5 μm, Shanghai, China) were provided by the Shanghai Aladdin Biochemical Technology Co., Ltd. The MgO and SiO<sub>2</sub> powders (AR, 3–5 μm, Beijing, China) were both provided by the Sinopharm Chemical Reagent Beijing Co., Ltd.

2.4. Analysis and characterization

The morphologies of the coatings before and after corrosion and the distribution of the elements were observed by scanning electron microscopy (SEM, Philips S-4800, Hitachi Ltd., Yokohama, Japan) with an attached energy dispersive spectrometer (EDS). SEM can also be used to measure the thickness of the emerging layer between Y<sub>2</sub>SiO<sub>5</sub> and the silicon layer after corrosion. The phase compositions of the coating in different states were characterized by X-ray diffraction (XRD, RIGAKU D/MAX-rB, Rigaku International Corp., Tokyo, Japan). The scanning rate of the XRD test was 5 °/min over the 20 range of 10°–90°.

3. Materials and methods

3.1. Comparison of Y<sub>2</sub>SiO<sub>5</sub>/Si TEBC before and after water oxygen corrosion

The weight change of the Y<sub>2</sub>SiO<sub>5</sub>/Si-coated SiCf/SiC substrate corroded in a 90% H<sub>2</sub>O/10% O<sub>2</sub> atmosphere at 1300 °C is shown in Figure 1. Y<sub>2</sub>SiO<sub>5</sub>/Si can persistently protect the SiCf/SiC substrate from corrosion.

| Table 1. Plasma spraying parameters used for the deposition of Y<sub>2</sub>SiO<sub>5</sub> coatings. |
|------------------------------------------|
| Parameter                        | Value       |
| Spraying current (A)               | 800         |
| Primary gas (Ar) flow (L.min<sup>-1</sup>) | 40          |
| Secondary gas (He) flow (L.min<sup>-1</sup>) | 14          |
| Carrier gas (Ar) flow (L.min<sup>-1</sup>) | 4.7         |
| Powder feed rate (RPM)             | 3.0         |
| Spray distance (mm)                | 80          |

Parameter Value
high-temperature water vapor for more than 193 h. The maximum weight gain per unit area is less than 0.4 mg/cm² throughout the entire corrosion test. In the initial stage of corrosion, there is a slight increase in weight per unit area. In the next few hours, the mass change versus time curve remains flat without obvious fluctuation. The curve drops suddenly when the accumulated corrosion time is over 193 h. The decline in the mass change versus time curve can be attributed to the partial peeling off of the Y₂SiO₅/Si coating. In our pre-experiment, the Y₂SiO₅/mullite mass change versus time curve can be attributed to the partial peeling off when the accumulated corrosion time is over 193 h. The decline in the temperature water vapor corrosion, the top photograph of the Y₂SiO₅ shown in Figure 2. Figure 2 (a) clearly shows that before high-potential against high-temperature water vapor.

The surface microstructure of the Y₂SiO₅/Si TEBC before and after water vapor corrosion in a 90% H₂O/10% O₂ atmosphere at 1300 °C is shown in Figure 2. Figure 2(a) clearly shows that before high-temperature water vapor corrosion, the top photograph of the Y₂SiO₅ layer is relatively flat. Almost all Y₂SiO₅ powders melt and spread well. After the 205-hour corrosion test, there are obvious corrosive traces on the surface and cross-section of the coating. The Y₂SiO₅ top layer combines with the Si bond layer well. The large defect area in the Si bond coating is caused by the accidental sample making process. Figure 2(b) shows the cross-section microstructure of the Y₂SiO₅/Si TEBC after corrosion. After 205 h of water vapor corrosion in a 90% H₂O/10% O₂ atmosphere at 1300 °C, the width and number of microcracks increased [24]. And the number of holes in the Y₂SiO₅ layer also increased. The EDS analysis result demonstrates that the emerging layer between the top layer and bond layer after corrosion is a thermally growing oxide (TGO) [17], which is made up of SiO₂.

The phases detected by XRD before and after the water vapor corrosion test are shown in Figure 4. The main phase in the coating before corrosion is Y₂SiO₅. There is also a small amount of Y₄.₆₇(SiO₄)₃O that exists in the coating. After the corrosion test, Y₄.₆₇(SiO₄)₃O accounted for the vast majority of the coating, and the amount of Y₂SiO₅ significantly decreased compared with the phase composition of the coating before corrosion. According to the Y₂O₃/OCUS phase diagram, when the Si content is reduced, Y₂SiO₅ will partially change to Y₄.₆₇(SiO₄)₃O. In addition, the study by Mechnich et al. also showed that in the Y–Si–O system, Si is essentially the mobile species. When the surface Si is converted into Si(OH)₄ and volatilized, the internal Si will move to the surface and generate Y₄.₆₇(SiO₄)₃O. The oxygen barrier ability of Y₄.₆₇(SiO₄)₃O is much lower than that of Y₂SiO₅. In addition, the cracks generated by the volume change accelerate the diffusion of O to the interior, and the coating loses the effect of blocking oxygen and water vapor.

3.2. Water vapor corrosion mechanism of Y₂SiO₅/Si coatings

Based on the experimental results and previous studies, we summarize the recession mechanism of Y₂SiO₅/Si coatings during the water vapor corrosion process. As depicted in Figure 5(a), during an early stage of the water vapor corrosion test, the Y₂SiO₅ top layer remains intact. There are almost no obvious defects on the surface and cross-section of the coating. The Y₂SiO₅ top layer commendably protects the bond layer and SiC/SiC substrate from high-temperature water vapor so that there is only slight weight gain during the early stage of corrosion.

The Y₂SiO₅/Si-coated SiC/SiC sample is removed from the tube furnace every 10 h to measure the variation in weight and flaking condition. After measuring, the sample is put back into the tube furnace for the next testing rotation. The taking-out and putting-back process during the test is accompanied by a great temperature change, which introduced great stress into the Y₂SiO₅/Si TEBC due to the different CTEs between the Y₂SiO₅ top layer (6.86 × 10⁻⁶/K) [22] and bond layer (4.5–5.5 × 10⁻⁶/K) [23]. With the influence of stress, a small number of microcracks in the Y₂SiO₅ top layer become wider and longer [24]. In addition, new cracks initiate as the test continues. Although the oxygen permeability in Y₂SiO₅ is low, there is still a small amount of oxygen penetrating through the top layer in the form of oxygen ions [25]. The molecular oxygen can also arrive at the interface between the top layer and bond layer along the generated cracks. The oxygen ions and the oxygen molecules will react with the silicon bond layer, leading to the formation of silica. Silica is also known as TGO. Not only oxygen but also water vapor can penetrate through the top layer along the cracks [17]. The water vapor reacts with TGO to form volatile Si(OH)₄, as shown in Figure 5(b). Besides, the TGO layer (10.3 × 10⁻⁶/K) [23] has a large mismatch of CTE with the Si layer and the Y₂SiO₅ layer, which can also lead to the generation of cracks. The weight gain caused by the oxidation of the bond layer and the weight loss caused by the volatilization of Si(OH)₄ cancel each other out. Therefore, the mass change versus time curve remains flat without obvious fluctuation before the accumulated corrosion time extends to 193 h. In short,
although the extension of cracks and the corrosion of the bond layer occurs, there is little impact on the total function of the Y$_2$SiO$_5$/Si coating. The Y$_2$SiO$_5$/Si coating still efficiently isolates the SiC$_f$/SiC substrate from water vapor.

When the corrosion test continued for over 193 h, the generated longitudinal and transverse cracks intersected with each other, forming a connected three-dimensional crack network. The high-temperature water vapor and oxygen easily arrive at the bond layer. Severe oxidation of the bond layer and volatilization of Si(OH)$_4$ occur, which deteriorates the bonding strength between the top layer and bond layer. Part of the Y$_2$SiO$_5$ layer peels off under the influence of stress. Therefore, the mass change versus time curve dramatically decreases when the corrosion time extends to 205 h. In addition, during the long period of the corrosion test, Y$_2$SiO$_5$ reacts with TGO to form Y$_{4.67}$(SiO$_4$)$_3$O, which is why a large amount of Y$_{4.67}$(SiO$_4$)$_3$O can be detected after the corrosion test [26]. Therefore, as shown in Figure 5(c), the proportion of Y$_2$SiO$_5$ decreases and the proportion of Y$_{4.67}$(SiO$_4$)$_3$O increases as the water vapor corrosion test continues.

### 3.3. Changing of Y$_2$SiO$_5$/Si TEBC after CMAS corrosion

Figure 6 (a)–(d) displays the cross-section microstructure of the Y$_2$SiO$_5$/Si TEBC corroded by CMAS at 1300 °C for 30 min, 1 h, 2.5 h and 4 h. Figure 5 shows that there is a dense reaction zone between the molten CMAS and Y$_2$SiO$_5$ top layer no matter how long the reaction continues. The thickness of the reaction zone increases as the reaction time increases.

Figure 7 displays the EDS linear scan result of the cross-section of the Y$_2$SiO$_5$/Si TEBC after 4 h of CMAS corrosion. There is no doubt that melted CMAS is rich in Ca, Mg, Al, and Si, and almost no Y can be detected. The reaction zone is also rich in Ca and Si. However, the proportions of Mg and Al dramatically drop in the reaction zone, and there is a slight increase in the amount of Y in the reaction zone. In the Y$_2$SiO$_5$ layer, the amount of Y rapidly increases, but the amount of Ca obviously decreases. The amount of Si also decreases to a certain degree in the Y$_2$SiO$_5$ layer.

It can be summarized from the variation of the elemental proportions shown in Figure 7 that Ca and Si in CMAS continuously permeate into Y$_2$SiO$_5$, leading to the formation of a reaction zone between melted CMAS and Y$_2$SiO$_5$. This reaction zone can effectively stop the mutual diffusion of elements in CMAS and Y$_2$SiO$_5$ [27, 28, 29]. Therefore, Y is not capable of diffusing into the reaction zone and the CMAS layer, and Mg and Al are only detected in the CMAS layer.

Figure 8 displays the phase composition of the mixture of Y$_2$SiO$_5$ and CMAS powders at a weight ratio of 1:1 after heating at 1300 °C for 30 min and 4 h, respectively. Figure 7(a) shows that after corrosion for 30 min at 1300 °C, Y$_{4.67}$(SiO$_4$)$_3$O and Ca$_3$Y$_2$(Si$_3$O$_9$)$_2$ can be detected from the mixture of CMAS and Y$_2$SiO$_5$. The content of Y$_{4.67}$(SiO$_4$)$_3$O is higher than that of Ca$_3$Y$_2$(Si$_3$O$_9$)$_2$. At the beginning of the CMAS corrosion test, a portion of the SiO$_2$ in CMAS reacts with Y$_2$O$_3$ in Y$_2$SiO$_5$, leading to the formation of Y$_{4.67}$(SiO$_4$)$_3$O. In addition, the remaining SiO$_2$ and CaO in CMAS react with Y$_2$SiO$_5$ to form a small amount of Ca$_3$Y$_2$(Si$_3$O$_9$)$_2$. The reaction equations mentioned above are described as Eqs. (1) and (2):

$$
\begin{align*}
\text{(a)} & \quad \text{H}_2\text{O} + \text{O}_2 & \quad \text{Y}_2\text{SiO}_3 \\
\text{SiC}_f/\text{SiC} & \quad \text{Si} \\
\text{SiO}_2 & \quad \text{SiC}_f/\text{SiC}
\end{align*}
$$

$$
\begin{align*}
\text{(b)} & \quad \text{H}_2\text{O} + \text{O}_2 & \quad \text{Y}_2\text{SiO}_3 \\
\text{SiC}_f/\text{SiC} & \quad \text{Si} \\
\text{SiO}_2 & \quad \text{SiC}_f/\text{SiC}
\end{align*}
$$

$$
\begin{align*}
\text{(c)} & \quad \text{H}_2\text{O} + \text{O}_2 & \quad \text{Y}_2\text{SiO}_5 \\
\text{SiC}_f/\text{SiC} & \quad \text{SiCOH}_4 \\
\text{SiO}_2 & \quad \text{SiC}_f/\text{SiC}
\end{align*}
$$

Figure 5. Recession mechanism of Y$_2$SiO$_5$/Si TEBC corroded in water vapor environment at (a) initial, (b) middle and (c) late stage.
When the mixture of CMAS and Y$_2$SiO$_5$ powders are kept at 1300 °C for 4 h, a large quantity of Ca$_4$Y$_6$O(SiO$_4$)$_6$ and a small amount of Ca$_3$Y$_2$(Si$_3$O$_9$)$_2$ are created, as shown in Figure 8. As the reaction time is prolonged, large amounts of CaO and SiO$_2$ are consumed. The remaining small amounts of CaO and SiO$_2$ react with Y$_2$SiO$_5$ to form Ca$_4$Y$_6$O(SiO$_4$)$_6$. The reaction equation is described as Eq. (3):

$$4\text{CaO} + 3\text{SiO}_2 + 3\text{Y}_2\text{SiO}_5 \rightarrow \text{Ca}_4\text{Y}_6\text{O}(\text{SiO}_4)_6$$  

The reaction of CMAS and Y$_2$SiO$_5$ powders can be described as:

$$2.335\text{Y}_2\text{O}_3(s) + 3\text{SiO}_2 \rightarrow \text{Y}_{4.07}(\text{SiO}_4)_3\text{O}$$  

$$3\text{CaO} + 5\text{SiO}_2 + \text{Y}_2\text{SiO}_5 \rightarrow \text{Ca}_3\text{Y}_2(\text{Si}_3\text{O}_9)_2$$  

Figure 6. Cross-section microstructure of Y$_2$SiO$_5$/Si TEBC corroded by CMAS at 1300 °C for (a) 30 min, (b) 1 h, (c) 2.5 h, (d) 4h.

Figure 7. EDS linear scan results of cross-section of Y$_2$SiO$_5$/Si TEBC after CMAS corrosion at 1300 °C for 4 h (a) overall scanning result, (b) Y, (c) Al, (d) Si, (e) O, (f) Ca, (g) Mg.
3.4. Reaction kinetics between CMAS and Y$_2$SiO$_5$/Si coatings

Table 2 lists the thickness of the reaction zone when Y$_2$SiO$_5$/Si TEBCs were corroded at 1200 °C, 1250 °C and 1300 °C for different times. Table 2 shows that at the same reaction temperature, as the reaction time is prolonged, the reaction zone becomes thicker. The thickness of the reaction zone also increases with the reaction temperature when the corrosion time is the same. In addition, at 1200 °C and 1250 °C, the reaction layer was thinner, and the reaction was slower. At 1300 °C, the reaction speed began to accelerate. The thickness of the reaction layer at different reaction times was consistent with previous studies, indicating the validity of the data [26–30].

![Figure 9. Thickness of reaction zone as a function of square root of oxidation time.](image)

Figure 9 plots the thickness of the reaction zone as a function of the square root of the oxidation time. The growth of the reaction zone seems to obey the parabolic law, shown as Eq. (4):

$$ y = kt^{1/2} + b $$

where $y$ is the thickness of the reaction zone, $t$ is the oxidation time, $k$ is the reaction rate constant, and $b$ is a constant. The fitting process is conducted on the thickness data listed in Table 2. According to the fitting result, the reaction rate constants at 1200 °C, 1250 °C and 1300 °C are 0.1466 μm·h$^{-1/2}$, 0.8425 μm·h$^{-1/2}$, and 1.9963 μm·h$^{-1/2}$, respectively. The reaction rate constant represents the growth rate of the reaction zone at different temperatures. When the CMAS corrosion test is conducted at 1200 °C, the growth rate of the reaction zone is very slow. As the reaction temperature increases to 1250 °C, the growth rate of the reaction zone increases more than four-fold compared with that at 1200 °C. When the corrosion temperature continues to rise to 1300 °C, the thickness of the reaction zone will dramatically increase more than twelve-fold compared with that at 1200 °C.

The obtained reaction rate constants at elevated temperatures are plotted in Figure 10. The apparent activation energy for the reaction between CMAS and the Y$_2$SiO$_5$ layer can be calculated using the Arrhenius formula as Eq. (5):

$$ k = k_0 \exp \left(\frac{-E}{2RT}\right) $$

where $E$ is the apparent activation energy for the CMAS corrosion test, $R$ is the ideal gas constant, and $T$ is the temperature of the CMAS corrosion test.

The natural logarithm of Eq. (5) is shown as Eq. (6):

$$ \ln k - \ln k_0 = -\frac{E}{2RT} $$

According to the fitting result shown in Figure 9, the relationship between the natural logarithm of the reaction rate constant and reciprocal temperature obeys a linear relation. The slope of the fitting line represents the apparent activation energy for CMAS corrosion, which is calculated to be 713.749 kJ/mol.

![Figure 10. Natural logarithm of reaction rate constant as a function of the inverse of temperature.](image)
4. Conclusions

Y$_2$SiO$_5$/Si-coated SiC/SiC was corroded by high-temperature water vapor and CMAS in this research. The Y$_2$SiO$_5$/Si TEBC can effectively separate the SiC/SiC substrate from water vapor at 1300 °C for over 205 h. After 250 h of water vapor corrosion, the majority of Y$_2$SiO$_5$ trans- forms into Y$_{4.67}$(SiO$_4$)$_3$O because of the reaction between Y$_2$SiO$_5$ and TGO. With the influence of TGO and cracks caused by stress, a portion of the Y$_2$SiO$_5$ top layer peels off along the TGO, causing the failure of the TGO. Ultimately leading to the formation of Ca$_4$Y$_6$O(SiO$_4$)$_6$ and Ca$_3$Y$_2$(Si$_3$O$_9$)$_2$ in the reaction zone. The Y$_{4.67}$(SiO$_4$)$_3$O is an intermediate as the test is executed at a high temperature. The apparent activation energy of the reaction is 713.749 kJ/mol, which can be used to predict the degree of reaction of CMAS corroding Y$_2$SiO$_5$ when the corrosion temperature is in the 1200–1300 °C temperature range. Overall, the findings obtained from this research are beneficial for screening appropriate materials for use as TEBCs to protect Si-based CMCs from high-temperature water vapor and CMAS corrosion.

Declarations

Author contribution statement

Qi Zhang: Performed the experiments; Wrote the paper.
Xueqin Zhang: Analyzed and interpreted the data; Wrote the paper.
Zhuang Ma; Ling Liu: Perceived and designed the experiments; Contributed reagents, materials, analysis tools or data.
Yanbo Liu: Performed the experiments; Contributed reagents, materials, analysis tools or data.
Wei Zheng: Performed the experiments; Analyzed and interpreted the data.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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