

Article

# Water Vapor Corrosion Behavior of Yb<sub>2</sub>SiO<sub>5</sub> Environmental Barrier Coatings Prepared by Plasma Spray-Physical Vapor Deposition

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**Abstract:** Tri-layer Si/mullite/Yb<sub>2</sub>SiO<sub>5</sub> environmental barrier coating (EBC) was prepared on the SiCf/SiC ceramic matrix composite (CMC) by plasma spray-physical vapor deposition (PS-PVD). The EBC samples were carried out with water vapor corrosion at 1300 °C for 200 h. After steam corrosion, Yb<sub>2</sub>SiO<sub>5</sub> layer forms a gradient porous structure. This is mainly due to the inclusion of SiO<sub>2</sub>-rich layer which is precipitated from the gasification inside the coating and existing a small amount of Yb<sub>2</sub>O<sub>3</sub> separately. During the corrosion process, water vapor infiltrates into the coating and reacts with the SiO<sub>2</sub> and Yb<sub>2</sub>O<sub>3</sub> to generate volatile substances. This forms a porous structure to make the coating brittle, resulting in mud cracks finally. In addition, the results show that the Yb<sub>2</sub>SiO<sub>5</sub> can react with the water vapor at the coating surface, forming an Yb<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> top layer.

Keywords: Yb<sub>2</sub>SiO<sub>5</sub> coating; EBC; water vapor corrosion; PS-PVD

# 1. Introduction

The high-performance aero-engines are developing in the direction of high thrust-weight ratio, high bypass ratio and high engine efficiency, which means the turbine inlet temperature will continue to rise [1]. Turbine inlet temperature of 1650 °C corresponds to a thrust weight ratio of 8. In order to increase the thrust weight ratio to 10–12, the temperature should raise to 1850 °C [2]. Therefore, traditional super alloys can no longer meet the needs of the next generation turbine engines. Silicon carbide (SiC) fiber-reinforced SiC ceramic matrix composite (SiCf/SiC CMC) has the advantages of low density, high strength and high temperature resistance [3,4]. It is considered as an alternative material for thermal components of the next generation turbine engines. However, in the fast combustion environment (e.g., water and oxygen, glass melt.), a rapid decline of the ceramic matrix will occur, leading to degradation of its advanced performance [5–7]. In order to solve the problem of premature failure of the SiC ceramic matrix composites in service environment, Lee et al. [8–10] have proposed the high-temperature protective environmental barrier coating (EBC).



Rare earth silicates (e.g., Yb, Er, Y, Lu) with good high temperature stability and good resistance to water vapor corrosion are considered to be the most potential EBC materials [11–13]. The thermal mismatch between Yb<sub>2</sub>SiO<sub>5</sub> and SiC CMC composites is effectively solved by the connection of Si antioxidant bond layer and 3Al<sub>2</sub>O<sub>3</sub>-2SiO<sub>2</sub> (Mullite) transition layer [14]. At present, tri-layer composite structure EBC is mainly prepared by atmospheric plasma spraying (APS), which is an efficient and low-cost preparation technology [15,16]. However, due to the limitations of the APS technology, such as its low power and fast jet flow, the spraying process is doped with a large number of un-melted or semi-molten particles which makes it difficult to obtain a dense coating system. The above coating defects provide channels for the steam corrosion coating and SiC substrate at high temperature and it seriously reduces the service life of the coating and substrate [17]. In recent years, plasma spray-physical vapor deposition (PS-PVD) has been widely used in preparation of high-temperature protective coatings (e.g., Thermal/environmental barrier coatings) due to its high power, low thermal stress and the characteristics of gas-liquid-solid multiphase composite deposition of layer/columnar structure coating through adjustment of parameter [18–20].

In this work, a tri-layer Si/Mullite/Yb<sub>2</sub>SiO<sub>5</sub> environmental barrier coating system was prepared on the SiCf/SiC CMC substrate by plasma spray-physical vapor deposition which is a novel coating preparation technology. The corrosion tests under high temperature and steam environment for a long time were carried out to analyze the microstructure and phase evolution of the coating. The protective effect of the dense environment barrier coating system on the substrate and its failure behavior was also investigated.

## 2. Experimental Methods

## 2.1. Preparation of the Coatings

Tri-layer Si/3Al<sub>2</sub>O<sub>3</sub>-2SiO<sub>2</sub>(Mullite)/Yb<sub>2</sub>SiO<sub>5</sub> dense environment barrier coatings was deposited in SiCf/SiC CMC (2 mm × 3 mm × 50 mm) by PS-PVD. Before spraying, the substrate was cleaned with ethanol. The thickness of Yb<sub>2</sub>SiO<sub>5</sub> top layer, Mullite transition layer and Si high-temperature oxidation resistant bonding layer were all controlled within 50 µm. In order to make the powder conductive, the powder was spread flat on the conductive tape and sprayed with gold to obtain its microstructure. Si (99%,  $-75 + 15 \mu$ m, signed 4810, see Figure 1a) and Mullite (99.9%,  $-45 + 5 \mu$ m, signed 6150, see Figure 1b) powder for spraying were purchased from Oerlikon-Metco Ltd. (Freienbach, Switzerland). In addition, agglomerated Yb<sub>2</sub>SiO<sub>5</sub> powders ( $-40 + 10 \mu$ m, Figure 1c) were prepared during this work through spray drying. Before deposition of each layer, the substrate was preheated (Si at 500 °C, Mullite at 1000 °C and Yb<sub>2</sub>SiO<sub>5</sub> at 830 °C) to avoid any defects such as microcracks which can be caused by the excessive stress due to phase change during the deposition process. The specific spraying parameters are shown in Table 1.



Figure 1. Micrographics of feed powders: (a) Si; (b) mullite and (c) agglomerated Yb<sub>2</sub>SiO<sub>5</sub> powders.

Coatings	Current/A	Ar/NLPM	He/NLPM	H <sub>2</sub> /NLPM	Feed Rate g/min	Stand-off Distance/mm	Pre-Heating Temperature/°C
Si	1650	110	-	6	8.2	450	500
Mullite	2600	70	50	-	10	1000	1000
Yb <sub>2</sub> SiO <sub>5</sub>	2600	100	20	-	20	1000	830

**Table 1.** Parameters of environmental barrier coatings (EBCs) fabricated by plasma spray-physical vapor deposition (PS-PVD).

## 2.2. Steam Corrosion

Prior to the water vapor corrosion, the as-sprayed coating needs to be oxidized at 1300 °C for 3 h [21]. Then, the heat-treated sample was placed in the steam corrosion device as shown in Figure 2 for 200 h at 1300 °C. The steam velocity in the tube furnace was about 0.2 m/s.



Figure 2. Schematic diagram of the steam corrosion device.

Field emitting-scanning electron microscope (FE-SEM, Nava-Nano-430, FEI, OR, USA) was used to observe the surface and cross-sectional microstructures of the coatings. X-ray diffraction (XRD, D8-Advance, Bruker,  $0.02^{\circ}$ /step, Cu-k $\alpha$ ,  $10^{\circ}$ –90°, Karlsruhe, Germany) was also used to analyze the phase evolution of the coating surface. Besides, the samples were examined using transmission electron microscope (TEM, Titan Themis 200, FEI, OR, USA) assisted with focused ion beam (FIB, SMI3050MS2, SII, Chiba, Japan) to determine the microstructures and distribution of element.

## 3. Results and Discussion

#### 3.1. EBCs Deposition

The cross-section microstructure of EBC is shown in Figure 3. It can be seen that in general, the coating is compact, and the layers are closely bounded together with no obvious pores and cracks. The interfaces between Yb<sub>2</sub>SiO<sub>5</sub> (CTE 7.23 × 10<sup>-6</sup> K<sup>-1</sup>), Mullite (CTE 5.48 × 10<sup>-6</sup> K<sup>-1</sup>) and Si (CTE  $3.5-4.5 \times 10^{-6}$  K<sup>-1</sup>) layers are clear. A good thermal compatibility is seen in Figure 3c,d. In the plasma flame flow, the temperature in some area is much higher than the melting point of Yb<sub>2</sub>SiO<sub>5</sub> leading to the decomposition of particles forming Yb<sub>2</sub>O<sub>3</sub> (~2346 °C) and SiO<sub>2</sub> (~1650 °C). In the deposition process, SiO<sub>2</sub> generates gas-solid transition and forms a small number of pores in the coating. The concentration of the two phases in the gas-liquid phases in the deposition process is significantly different due to their different melting points. This leads to the distinct stratification during the deposition process as shown in Figure 3b.



**Figure 3.** Back scattering electron(BSE) microstructures micrographs of EBC: (**a**) multi-layer structure; (**b**) Yb<sub>2</sub>SiO<sub>5</sub> coating; (**c**) Interface of Yb<sub>2</sub>SiO<sub>5</sub> and Mullite; (**d**) Interface of Mullite and Si.

The raw powder of ytterbium silicate layer was prepared by solid phase reaction (ytterbium oxide and silicon oxide were sintered at 1800 °C). The X-ray diffraction (XRD) pattern of the ytterbium silicate before and after spraying shown in Figure 4 suggests that there has been high-temperature decomposition in the spraying process. The original powder is a standard ytterbium silicate monocline phase (Stable phase, PDF 40-0386). However, in the high temperature of the plasma flame flow in non iso-thermal temperature field during the process of spraying, ytterbium silicate was formed (Unstable phase, PDF 52-1187) [22]. In addition, there is Yb<sub>2</sub>O<sub>3</sub> on the surface of as-sprayed Yb<sub>2</sub>SiO<sub>5</sub> coating as reflected in the XRD spectrum diffraction peaks obviously. This indicates that in the spraying process, part of the ytterbium silicate in the local high temperature region occurred thermal decomposition (Equation (1)).

$$Yb_2SiO_5(s) \to Yb_2O_3(s) + SiO_2(g). \tag{1}$$

The gasification point of SiO<sub>2</sub> is about 2230 °C which is lower than the temperature of plasma beam flow, leading to the loss of silica gasification. Since the unstable phase is not stable at high temperature (~1300 °C), it can be easily changed to the ytterbium silicate with a stable structure. Therefore, after spraying, the coating needs to be kept at 1300 °C for 3 h to transform into the stable phase. The phase changed during the heat treatment and the crystallinity of Yb<sub>2</sub>SiO<sub>5</sub> after recrystallization is lower than that of the original powder.



**Figure 4.** X-ray diffraction (XRD) patterns of Yb<sub>2</sub>SiO<sub>5</sub> agglomerate powders, as-sprayed coating and annealed coating.

## 3.2. Water Vapor Corrosion

Figure 5 shows the surface microstructure evolution of the coating under different vapor phase corrosion time. As shown in Figure 5a1, the coating in the spraying state is relatively dense, with a small amount of molten micro-plane particles deposited on the surface. The enlarged shows that the surface is mainly composed of agglomerated nanoparticles due to the dispersion of agglomerated Yb<sub>2</sub>SiO<sub>5</sub> powder in the carried gas and plasma. This has changed from solid to gas-liquid mixed phase and then was formed by recrystallization. In longer corrosion time, no obvious change in the coating surface is observed by the low power scanning electron microscopy (SEM). However, observing the surface corrosion of the steam after 50 h under the high magnification SEM shows that the number of grains had been significantly decreased and the microcosmic surface has changed to smooth oxide form (i.e., silica and ytterbium oxide). The internal coating reacts with water vapor on the surface and forms a few escape holes. After 100 h corrosion,  $Yb_2SiO_5$  sample is oxidized in the steam environment and there is obvious contrast bulge at the grain boundary on the surface. These ridges were formed by the volatilization of silica in the unstable corrosive medium Yb<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>, leaving a stable Yb-monosilicate [13]. After 200 h of steam exposure, it can be seen from Figure 5d1,d2 that the ridge structure gradually decreases, and a few cracks are appeared on the surface. The porous structure increases the brittleness of the coating and produces stress cracks. In addition, a large number of discrete bright spot particles can be observed under the high power scanning electron microscope since corundum tube is exposed to the high-temperature steam over a long period of time. Alumina also reacts with the water vapor to produce gas products, which are transferred to the coating and react with the coating surface to form nanoparticles.



**Figure 5.** Scanning electron microscope (SEM) images of Yb<sub>2</sub>SiO<sub>5</sub> coating surface morphology after steam corrosion at 1300 °C for different time: (**a1,a2**) as-sprayed; (**b1,b2**) steam corrosion for 10 h; (**c1,c2**) steam corrosion for 100 h; (**d1,d2**) steam corrosion for 200 h.

The XRD patterns of the coatings after different corrosion time are shown in Figure 6. At longer exposed time, the diffraction peak of  $Yb_2SiO_5$  becomes gradually weaker, indicating that its relative content decreases due to the steam corrosion reaction as shown in Equations (2) and (3). In addition,  $Yb_2SiO_5$  grains also grew in the high temperature environment seen in Figure 5d2. The corrosion mesophase of  $Yb_2Si_2O_7$  accumulates on the surface, which could be confirmed from the gradual enhancement of its diffraction peak:

$$2Yb_2SiO_5(s) + 3H_2O(g) \rightarrow Yb_2Si_2O_7(s) + 2Yb(OH)_3(g),$$
(2)

$$Yb_2Si_2O_7(s) + 2H_2O(g) \rightarrow Yb_2SiO_5(s) + Si(OH)_4(g).$$
(3)

The surface phase is mainly dominated by  $Yb_2SiO_5$  and  $Yb_2O_3$  before the corrosion. After water vapor corrosion, the  $Yb_2SiO_5$  and  $Yb_2O_3$  content in coating surface significantly decreased, especially the  $Yb_2O_3$  which is no residue on the surface. At 200 h corrosion, the  $Yb_3Al_5O_{12}$  peaks appear because under the environment of high temperature and water vapor,  $Yb_2O_3$  reacts with water, as well as with  $Al_2O_3$  from the corundum tube (Equations (4) and (5)). The results are consistent with Richards that the corundum tube interferes with the testing process [23]:

$$Yb_2O_3(s) + 3H_2O(g) \rightarrow 2Yb(OH)_3(g), \tag{4}$$

$$3Yb_2O_3(s) + 5Al_2O_3(s) \rightarrow 2Yb_3Al_5O_{12}(s).$$
 (5)



Figure 6. XRD patterns of different corrosion duration.

The cross-section microstructure of Si/Mullite/Yb<sub>2</sub>SiO<sub>5</sub> environmental barrier coatings after 200 h of water vapor corrosion is shown in Figure 7. In general, the adhesive layers (Si/Mullite) and the substrate are not obviously eroded after the coating was exposed to the steam for such a long time. This indicates that Yb<sub>2</sub>SiO<sub>5</sub> barrier layer has a good water-oxygen permeability resistance. However, many pores area are appeared inside the coating. Mud-cracks are also appeared throughout Yb<sub>2</sub>SiO<sub>5</sub>. The pores are mainly concentrated in the upper layer of ytterbium silicate as shown in Figure 7a. The reason is that a large amount of SiO<sub>2</sub> is mixed with gasification and decomposition inside the coating and constantly reacts with the water vapor in the tube furnace (Equation (6)) to generate volatile gas Si(OH)<sub>4</sub>.

$$3\mathrm{SiO}_2(\mathrm{s}) + 12\mathrm{H}_2\mathrm{O}(\mathrm{g}) \to 6\mathrm{Si}(\mathrm{OH})_4(\mathrm{g}). \tag{6}$$

This continuously penetrates and corrode inside the coating and forms a network and porous structure resulting in brittle cracks inside the coating. In addition, ytterbium oxide, which exists separately in the coating, also reacts with the water vapor.

It can be clearly seen in the BSE mode that the coating has a significant corrosion reaction layer near the surface from the Figure 7c. The energy disperse spectroscopy (EDS) elemental analysis was conducted on the dark upper layer (point 1) and lower layer (point 2). The element content ratio of Yb, Si and O indicates that the dark reaction layer is mainly Yb<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>, while the lower reaction layer is Yb<sub>2</sub>SiO<sub>5</sub>. The above conclusions also verify the XRD analysis results in Figure 6.



**Figure 7.** Cross-sectional micrographs of the coatings after 200 h water vapor corrosion: (**a**) overview EBCs; (**b**) interface of Yb<sub>2</sub>SiO<sub>5</sub> and Mullite; (**c**) near-surface of Yb<sub>2</sub>SiO<sub>5</sub> layer; (**d**,**e**) Energy dispersive spectrometer(EDS) elemental analysis.

# 3.3. Analysis of the Steam Corrosion Behavior

Dense EBCs can be prepared by PS-PVD. However,  $Yb_2SiO_5$  can be easily transformed into unstable US-Yb\_2SiO\_5 under the high temperature (~4000 °C) [24] and ultra-low pressure (~150 Pa) during the process. In addition, some of the powder can be decomposed into ytterbium oxide and silicon oxide. State changes of Yb\_2SiO\_5 particles during the spraying are shown in Figure 8. This process can be divided into three steps—firstly, under the impact of carrier gas, the ytterbium silicate aggregated powder was dispersed into micro nanoparticles; Then, the lattice distortion occurs under the combined action of high temperature plasma beam and ultra-low pressure. In the energy concentration region of the beam center, the microscopic stress of unstable phase is decomposed into ytterbium oxide and silicon oxide. Due to the different density of these materials, the distribution in the beam has obvious gradient and expansion and dissipation of part of the gas SiO<sub>2</sub>; therefore, deposition morphology on the substrate also shows obvious layered structure.



Figure 8. Dynamic changes of Yb<sub>2</sub>SiO<sub>5</sub> particles in the plasma beam using PS-PVD.

Figure 9 shows the transmission electron microscope (TEM) analysis results of the ytterbium silicate sprayed layer. The layer has light and dark stripes generated by different element distribution. There are also a few holes concentrated near the dark stripes. In order to quantify the element differences in the stripes with different contrast degrees and determine the phase composition of different layers, EDS analysis was conducted. Figure 9c–f also show the element plane scanning and point analysis conducted on the selection in Figure 9b. The results indicate that  $Yb_2SiO_5$  decomposition did exist in the deposition process. Due to the different gasification temperatures of  $Yb_2O_3$  and  $SiO_2$ , the vapor  $SiO_2$  formed after decomposition contracted in volume after solidification, so obvious pores were formed.  $Yb_2O_3$  and  $Yb_2SiO_5$  are dispersed in the coating seen in Figure 9f.



**Figure 9.** Microstructure and element analysis of Yb<sub>2</sub>SiO<sub>5</sub> coating: (**a**) Bright field transmission electron microscope (TEM) image of Yb<sub>2</sub>SiO<sub>5</sub> coating; (**b**) dark field magnification of figure **a**; (**c**–**e**) EDS mapping of figure **b** showing Si, Yb; (**f**) magnified TEM image of figure **a**; (**g**–**i**) EDS element analysis of points 1, 2 and 3 in figure **f**.

AS-sprayed EBC samples were subjected to the heat treatment at 1300 °C for 3 h and the partially decomposed ytterbium oxide and silicon oxide were regenerated through the solid phase reaction to form stable ytterbium silicate. The sample was placed in the corrosion device shown in Figure 2 (1300 °C, 200 h, 0.2 m/s) and the section morphology after corrosion is shown in Figure 10. The composition and structural evolution of Yb<sub>2</sub>SiO<sub>5</sub> coating under high temperature water vapor were analyzed by TEM. Sample blocks 15  $\mu$ m deep were excavated on the near-coated surface by FIB. It can be seen that a reaction layer of 3–5  $\mu$ m was formed on the surface and a network of porous structures formed by steam corrosion exists below the reaction layer. This structure generates greater stress, leading to more microscopic cracks. The Yb<sub>2</sub>SiO<sub>5</sub> coating after 200 h corrosion is divided into two zones—(I) surface reaction zone, which is connected with the external steam environment; (II) vapor permeable corrosion layer, where the vapor permeated into the coating and reacted with the decomposition products Yb<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> to form Yb(OH)<sub>3</sub> and Si(OH)<sub>4</sub>.



Figure 10. (a) TEM analysis area cut by FIB; (b) Bright field image of figure a.

The corrosion process of the top coating under high temperature water vapor will be analyzed from the coating surface to the CMC matrix. After 200 h of corrosion, it produced equiaxed crystals with obvious grain boundaries on the surface of the coating, as shown in Figure 11a. Based on the previous analysis results, the white nanocrystals which were aluminum oxide nanoparticles brought by the external environment. Through the analysis of the elements and phase of the near surface area I, Al elements from the surface to the coating permeability, as shown in Figure 11b. For the surface reaction zone under TEM bright field, the large amounts of nano grain accumulation growth. The area I is composed of two phases according to the EDS analysis—one is the Al-rich phase and the other is Si-rich phase. Yb and O no obvious difference in the two phase distribution. The surface grains were analyzed further by selective area electron diffraction (SAED). After calculation and analysis, the Al-rich phase is Yb<sub>3</sub>Al<sub>5</sub>O<sub>12</sub>, while the Si-rich phase is Yb<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>, which was consistent with the XRD phase analysis results on the surface at 200 h. No significant Al-phase was found inside the coating of Yb<sub>2</sub>SiO<sub>5</sub>, indicating that Al was transferred from the outside (corundum heating tube and furnace plug) to the coating surface and reacted.



**Figure 11.** Phase analysis of surface reaction zone I: (**a**) cross-sectional dark field image of grain growth layer in zone I; (**b**–**e**) Al, Si, Yb and O elements EDS mapping of zone I; (**f**) SEM of surface reaction layer; (**g**) Selected area electron diffraction(SAED) of rich-Al grains in Zone I and (**h**) SAED of none-Al grains in Zone I

Below the surface reaction zone is the internal corrosion zone II. As shown in Figure 12, After 200 h of corrosion, network holes were formed. At the same time, due to the reaction, a large amount of internal stress is generated, resulting in more microscopic cracks in the coating. The coating of ytterbium silicate after corrosion in TEM bright field images had a typical reticulated porous structure and there were still light and dark phase streaks similar to that of the as-sprayed coating as shown in Figure 12a. Elemental analysis of this region shows that the bright fringe is a Yb-rich phase with high O content, while the dark fringe contains more Si element. The phase structure of the light and dark fringe phase was analyzed by selecting diffraction. After calculation and analysis, the PDF-22019 database was used for the comparison of crystal surface spacing and the dark fringe was confirmed as Yb<sub>2</sub>SiO<sub>5</sub>. The bright fringe represents the phase Yb<sub>2</sub>O<sub>3</sub>. The pores are mainly concentrated in the bright streaks, which in the coating, the rare earth decomposition products cannot be stable in the high-temperature water vapor, forming gaseous products volatilization. There was no SiO<sub>2</sub> residue, so water vapor reacted preferentially with SiO<sub>2</sub> to produce Si(OH)<sub>4</sub> and then with Yb<sub>2</sub>O<sub>3</sub> to produce Yb(OH)<sub>3</sub>, which destroyed the structural integrity of the coating, resulting in holes and cracks.



**Figure 12.** Phase and element analysis in II internal corrosion zone: (**a**) bright field image in zone II; (**b–d**) Yb, Si and O elements scanning in figure **a**; (**e–f**) morphology and SAED analysis of dark fringe phase in figure **a**; (**g–h**) microstructure and SAED analysis of bright fringe in figure **a**.

Based on the above characterization and analysis, we established the physical model shown in Figure 13 to reflect the corrosion behavior of ytterbium silicate coating prepared by PS-PVD when exposed to water vapor at 1300 °C for 200 h. The corrosion is divided into two stages—(1) The early stage, due to the thermal decomposition of ytterbium silicate during the spraying process, a large number of Yb<sub>2</sub>O<sub>3</sub> nanoparticles (SiO<sub>2</sub> has volatilized) were collected on the surface, which reacted with water vapor first. After the reaction, the coating surface became dense and smooth and the main component was ytterbium silicate; (2) The later corrosion, when Yb<sub>2</sub>O<sub>3</sub> on the surface reaction is completed, the water vapor begins to corrode and permeate along the coating microcrack and the oxide aggregation area decomposed in the coating. At this time, the Yb<sub>2</sub>SiO<sub>5</sub> coating produces a network of porous channels gradually densified from the surface to the inside of it. With the prolonged time of vapor exposure, a large amount of vapor accumulated on the surface of the coating, except a small part of vapor penetrated into the interior of the coating. Combined with the change results of the surface phase and EDS element analysis, it was speculated that a slow reaction occurred on the surface

(Equations (2) and (3)) and the transition product  $Yb_2Si_2O_7$  accumulated on the surface, forming a dense equiaxed crystal region. In addition, in the long-term high temperature environment, the interdiffusion zone between  $Yb_2SiO_5/Mullite$  coating interfaces will also occur and  $Yb_2SiO_5$  and  $Al_2O_3$ react to form a bar-shaped  $Yb_3Al_5O_{12}$  [25]. Eventually, corrosion holes in the coating of ytterbium silicate extend into the bonding layer, which will result in the coating and CMC matrix fail quickly.



Figure 13. Structural evolution model of vapor corrosion of Yb<sub>2</sub>SiO<sub>5</sub> coating.

# 4. Conclusions

High-power plasma spray-physical vapor deposition was used to prepare compact and stable Si bonded oxidation layer and Mullite transition layer. However, during the deposition of ytterbium silicate top layer, the stable monocline ytterbium silicate phase was transformed into an unstable phase structure or even decomposed to form layered coating with typical element gradient (due to the high saturated vapor pressure of SiO<sub>2</sub>). The corrosion failure behavior of the coating system in steam environment at the same temperature after heat treatment at 1300 °C was studied. The results show that ytterbium silicate has good temperature stability and water vapor corrosion resistance. However, the top-coating decomposition of ytterbium silicate damaged the coatings. In the 1300 °C water vapor environment, the vapor reacts with the decomposed inclusions in the coating and continuously penetrates into the substrate forming a porous network structure. This makes the coating structure brittle and generates microscopic cracks. It is concluded that compact environmental barrier coatings can be prepared by plasma spray-physical vapor deposition. However, in order the coating to be perfect, the related parameters need to be optimized to improve the decomposition of ytterbium silicate.

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