Interaction of multicomponent disilicate $(\text{Yb}_{0.2}\text{Y}_{0.2}\text{Lu}_{0.2}\text{Sc}_{0.2}\text{Gd}_{0.2})_2\text{Si}_2\text{O}_7$ with molten calcia–magnesia–aluminosilicate

Yu DONG^{a,†}, Ke REN^{b,†}, Qiankun WANG^a, Gang SHAO^c, Yiguang WANG^{b,*}

^aScience and Technology on Thermostructural Composite Materials Laboratory,
Northwestern Polytechnical University, Xi'an 710072, China

^bInstitute of Advanced Structure Technology, Beijing Institute of Technology, Beijing 100081, China

^cHenan Province Industrial Technology Research Institute of Resources and Materials,
Zhengzhou University, Zhengzhou 450001, China

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Abstract: Environmental barrier coating (EBC) materials that are resistant against molten calcia–magnesia–aluminosilicate (CMAS) corrosion are urgently required. Herein, multicomponent rare-earth (RE) disilicate $((\text{Yb}_{0.2}\text{Y}_{0.2}\text{Lu}_{0.2}\text{Sc}_{0.2}\text{Gd}_{0.2})_2\text{Si}_2\text{O}_7, (\text{5RE})_2\text{Si}_2\text{O}_7)$ was investigated with regard to its CMAS interaction behavior at 1400 °C. Compared with the individual RE disilicates, the $(\text{5RE})_2\text{Si}_2\text{O}_7$ material exhibited improved resistance against CMAS attack. The dominant process involved in the interaction of $(\text{5RE})_2\text{Si}_2\text{O}_7$ with CMAS was reaction-recrystallization. A dense and continuous reaction layer protected the substrate from rapid corrosion at high temperatures. The results demonstrated that multicomponent strategy of RE species in disilicate can provide a new perspective in the development of promising EBC materials with improved corrosion resistance.

Keywords: environmental barrier coating (EBC) materials; rare-earth (RE) disilicates; multicomponent ceramics; calcia–magnesia–aluminosilicate (CMAS) interaction

1 Introduction

SiC-based ceramic matrix composites (CMC-SiC) are promising candidates to replace Ni-based superalloys for application in engine hot sections due to their superior specific strength and oxidation resistance at elevated temperatures [1,2]. However, the harsh service environment involves the generation of large volumes of combustion gas, especially water vapor, which leads to the corrosion of CMC-SiC materials, resulting in fast mass loss and

a subsequent decrease in performance [2]. A dense environmental barrier coating (EBC) is commonly applied on CMC-SiC materials to alleviate the damage from volatilization of the oxidized product of silica in a high-velocity water vapor environment. Furthermore, with the increase in engine service temperatures, there is also the danger of corrosion from siliceous debris, also named calcia–magnesia–aluminosilicate (CMAS), in the form of volcanic ash, airborne sand, and runaway debris [2–5]. Thus, ideal EBC materials should also effectively alleviate CMAS corrosion of the CMC-SiC matrix at high temperatures.

Molten CMAS attached to a coating surface can substantially reduce the high temperature capability of EBCs and compromise their performance through a

[†] Yu Dong and Ke Ren contributed equally to this work.

* Corresponding author.

E-mail: wangyiguang@bit.edu.cn

CMAS–EBC interaction. Thus, new EBC materials that are resistant to molten CMAS corrosion are urgently required [2–6]. Rare-earth (RE) disilicates are considered as promising materials for EBC applications due to their good corrosion resistance, similar coefficient of thermal expansion (CTE) as CMC–SiC, and excellent high-temperature stability [7–11]. For instance, β -RE₂Si₂O₇ (RE = Sc, Lu, and Yb) and γ -Y₂Si₂O₇ showed similar CTEs to SiC [7] and no polymorphs at elevated temperatures [8–11], both of which are key requirements for EBC materials. The interaction behavior of individual RE-disilicates with molten CMAS has been previously explored [11–15]. For individual RE₂Si₂O₇ materials, different propensities for reaction-crystallization into apatite were observed due to the varying affinities between the RE elements and Ca. The mechanisms of reaction-crystallization or penetration into grain boundaries depend mainly on the different RE-disilicates and interaction temperatures.

Previous studies reported that RE-disilicate solid solutions exhibited improved corrosion resistance as well as the physical properties required for EBC applications [11,16]. Binary RE-disilicate solid solutions showed better thermo-physical properties than the individual RE-disilicate [11]. Further, ternary RE-disilicate (Y, Yb, Lu)₂Si₂O₇ solid solutions exhibited a higher resistance to corrosion in a water vapor gas stream than the individual RE-disilicate counterparts [16]. When the number of principal RE elements with relatively high concentration is higher than 4, a multicomponent RE-disilicate is formed, which is also called a high-entropy disilicate. The high-entropy concept originated from high-entropy alloys, wherein five or more elements with an equiatomic or near-equiatomic ratio form a single phase [17]. In the high-entropy system, the multiple principal elements with equiatomic or near-equiatomic ratio would increase the configuration entropy of mixing, thereby stabilizing the solid solution [18–20]. The concept was extended to ceramics, including oxides [21–23], borides [24–27], carbides [28–30], and silicide [31,32]. Through the high-entropy effect, these ceramics showed improved mechanical properties [26,28–30,33,34], thermophysical properties [34–39], and robust corrosion resistance [40–42]. The recently developed multicomponent RE-disilicates [41–44] also showed better water vapor resistance at high temperatures, lower thermal conductivity, and better mechanical properties than the individual RE-disilicates, attributed to the high-entropy effect. Especially, Sun *et al.* [44] reported that a multicomponent γ -type (Gd_{1/6}Tb_{1/6}Dy_{1/6}Tm_{1/6}Yb_{1/6}Lu_{1/6})₂Si₂O₇ disilicate

presented no polymorph transition until melting point. As summarized in previous reports [17,45], four core effects take place in high-entropy materials: (1) high-entropy effect; (2) severe lattice distortion effect; (3) sluggish diffusion effect; and (4) “cocktail” effect due to their unique composition design.

CMAS corrosion on RE-disilicate could theoretically be controlled by RE element diffusion and reaction with the CMAS. The sluggish diffusion effect and “cocktail” effect in multicomponent RE-disilicates would play a key role in their CMAS corrosion behavior [41,42]. It is recognized that multicomponent RE-disilicates can show good resistance to CMAS corrosion at high temperatures. Therefore, a multicomponent RE-disilicate EBC (Yb_{0.2}Y_{0.2}Lu_{0.2}Sc_{0.2}Gd_{0.2})₂Si₂O₇ ((5RE)₂Si₂O₇) was prepared herein to study its interaction with molten CMAS at 1400 °C. The phases and morphologies of specimens were characterized following their exposure to molten CMAS for various durations. The results of this study can provide insights into the underlying mechanism of reaction between (5RE)₂Si₂O₇ and CMAS as well as delineate a promising strategy for the design and development of potential EBCs with good properties.

2 Experimental

2.1 Material preparation

(5RE)₂Si₂O₇ powders were synthesized with different Si to RE molar ratios (1, 1.1, 1.15, and 1.2), in order to achieve a pure, single disilicate phase. A sol–gel process combined with solid-state reaction was employed to prepare the multicomponent powders. The detailed process has been described in our previous work [41]. The as-obtained powders were pressed into pellets with a diameter of ~13.5 mm and a thickness of ~2 mm using a uniaxial pressure of 10 MPa, followed by cold isostatic pressing at 200 MPa for 5 min. The as-pressed pellets were sintered at 1600 °C for 3 h to obtain (5RE)₂Si₂O₇ bulks. Y₂Si₂O₇ and Gd₂Si₂O₇ bulks were also prepared for comparison through the same process.

The CMAS used herein had a composition of CaO, MgO, AlO_{1.5}, and SiO₂ in the molar ratio of 33 : 9 : 13 : 45. The raw CaO, MgO, AlO_{1.5}, and SiO₂ materials were of analytical reagent grade and purchased from Tianli Chemical Reagent Co., Ltd. (Tianjin, China). The raw materials were uniformly mixed, followed by heat-treatment at 1200 °C for 2 h in an alumina crucible to form the CMAS powders. The as-prepared CMAS powders were

ball-milled and pressed into pellets with diameter of 13.5 mm and thickness of 2 mm under uniaxial pressure of 10 MPa for 60 s, followed by cold isostatic pressing at 200 MPa for 5 min [12].

2.2 CMAS corrosion

Assessment of the interaction of CMAS with the prepared materials was performed at 1400 °C at different exposure time (0, 2, 4, 5, 10, and 20 h) by placing one quarter of a CMAS pellet on the top of EBC bulk inside a ZrO₂ crucible. Following exposure to CMAS, the corroded bulks were cut into halves using a low-speed saw, and the cross-sections were polished to 1 μm finish. In addition, the CMAS powders were mixed with (5RE)₂Si₂O₇, Y₂Si₂O₇, and Gd₂Si₂O₇ powders in a 1 : 1 weight ratio using ball-milling. The obtained powders were then pressed into pellets as described above, followed by heat-treatment at 1400 °C for 4 h in a ZrO₂ crucible.

2.3 Characterization

The as-synthesized (5RE)₂Si₂O₇ powders with different molar ratios of RE to Si and the heat-treated disilicate–CMAS mixture pellets were characterized by X-ray diffraction (XRD; Rigaku D/max-2400, Tokyo, Japan). The cross-section of the CMAS-interacted samples was observed by scanning electron microscopy (SEM; Helios G4 CX, FEI, USA) along with energy-dispersive spectroscopy (EDS; ThermoFisher, Thermo NS7, USA).

3 Results

The XRD patterns of the synthesized (5RE)₂Si₂O₇ powders for all Si to RE molar ratios show that a disilicate phase with a β polymorph structure was obtained (Fig. 1). Further, among the five individual

RE-disilicates considered here, Yb₂Si₂O₇, Lu₂Si₂O₇, and Sc₂Si₂O₇ exhibited a β polymorph until their melting point, whereas Y₂Si₂O₇ and Gd₂Si₂O₇ underwent a polymorphic phase transformation during heating [9,11]. It is believed that the different crystal structures of individual RE-disilicates form a single phase in multicomponent (5RE)₂Si₂O₇ due to the high entropy effect [41–44]. The presence of a single β polymorph (5RE)₂Si₂O₇ indicated that the multicomponent disilicate would have good high-temperature stability, which is crucial for the application of EBCs.

Different Si to RE ratios were tested to achieve a pure (5RE)₂Si₂O₇ phase. At a stoichiometric ratio of Si to RE, a monosilicate phase (RE₂SiO₅) was observed, while a SiO₂ phase was detected when the silicon content was high (Si : RE = 1.2 : 1) (Fig. 1(a)). At a Si to RE ratio of 1.15, the (5RE)₂Si₂O₇ phase was almost pure β polymorph with a trace of silica. Therefore, this composition was chosen herein for further study. The sintered (5RE)₂Si₂O₇ bulk had a relative density of about 95%, and the morphology of the polished (5RE)₂Si₂O₇ pellet showed no obvious cracks or pores in the bulk due to excess SiO₂ filling in the pores (Fig. 1(b)). As indicated in the inset EDS images, the light-color phase is (5RE)₂Si₂O₇ and the gray phase is believed to be SiO₂. Excess SiO₂ is usually required to form a pure disilicate phase [12], and may also eliminate potential cracking or pore formation in the RE-disilicate matrix.

The cross-sectional morphology of the (5RE)₂Si₂O₇ pellet after interaction with CMAS at 1400 °C for 4 h showed three zones: a thick CMAS region on the top, a reaction zone in the middle, and the (5RE)₂Si₂O₇ substrate (Fig. 2(a)). The reaction zone was dense and continuous, with a minimal appearance of pores or cracks. EDS analysis (Fig. 2(b)) shows an abundance of Ca element in the reaction zone, assumed to be mainly derived from the chemical reaction between CaO in CMAS

Fig. 1 (a) XRD patterns of (5RE)₂Si₂O₇ at different Si to RE ratios and (b) SEM image of (5RE)₂Si₂O₇ at Si to RE ratio of 1.15 : 1, and EDS images of (5RE)₂Si₂O₇ and SiO₂ were insetted.

Fig. 2 (a) Cross-sectional SEM images at low magnification and (b) EDS elemental mappings of $(5\text{RE}_{0.2})_2\text{Si}_2\text{O}_7$ specimen after CMAS corrosion at 1400°C for 4 h.

and $(5\text{RE})_2\text{Si}_2\text{O}_7$. XRD analysis (Fig. 3(a)) indicates that the Ca-containing reaction product of CMAS and $(5\text{RE})_2\text{Si}_2\text{O}_7$ was a single $\text{Ca}_3\text{RE}_2(\text{Si}_3\text{O}_9)_2$ cyclosilicate phase. The reaction product was also characterized by EDS (Fig. 4(a) Point C and Table 1), and the composition of reaction product roughly corresponded to $\text{Ca}_3\text{RE}_2(\text{Si}_3\text{O}_9)_2$ cyclosilicate. The reaction product also contained a trace of Al element, arising from the cyclosilicate–Al solid solution or from the reaction products between Al and RE elements [14,15].

Two sub-layers were observed in the enlarged morphologies of the reaction zone (Figs. 4(a) and 4(b)): a dense reaction-product sublayer close to the CMAS top layer and a penetration sublayer near the $(5\text{RE})_2\text{Si}_2\text{O}_7$ substrate. The reaction-product sublayer was $\sim 16\ \mu\text{m}$ in depth and was composed of the reaction products, e.g., $\text{Ca}_3\text{RE}_2(\text{Si}_3\text{O}_9)_2$ cyclosilicate. The penetration sublayer

consisted of the substrate phase (Fig. 4(b) Point D and Table 1), pockets of CMAS glass replacing the original SiO_2 sites, $\text{Ca}_3\text{RE}_2(\text{Si}_3\text{O}_9)_2$ generated after reaction with $(5\text{RE})_2\text{Si}_2\text{O}_7$ substrate (Fig. 4(b) Point F and Table 1), and small amounts of residual SiO_2 (Fig. 4(b) Point E and Table 1). To reduce the uncertainty in the measurement, no less than 30 measurement points were employed to obtain the depth of reaction-product sublayer and penetration sublayer.

The CMAS region on the top was formed by molten CMAS pellets on the $(5\text{RE})_2\text{Si}_2\text{O}_7$ after corrosion testing. Based on EDS analysis (Fig. 4(a) Point A and Table 1), this region was mainly composed of molten CMAS glass with a small amount of RE elements. Dendritic areas with main composition of RE elements, Ca, Si, and O (Fig. 4(a) Point B and Table 1) were also detected in the CMAS region. Based on the molar ratio of the

Fig. 3 XRD patterns of CMAS-interacted specimens: (a) $(5\text{RE}_{0.2})_2\text{Si}_2\text{O}_7$, (b) $\text{Y}_2\text{Si}_2\text{O}_7$, and (c) $\text{Gd}_2\text{Si}_2\text{O}_7$.

Fig. 4 Cross-sectional SEM images of CMAS-interacted specimens at 1400 °C for 4 h at (a) low and (b) high magnifications for $(5\text{RE}_{0.2})_2\text{Si}_2\text{O}_7$, (c) $\text{Y}_2\text{Si}_2\text{O}_7$, and (d) $\text{Gd}_2\text{Si}_2\text{O}_7$.

Table 1 Average EDS results of the selected zones in $(5\text{RE}_{0.2})_2\text{Si}_2\text{O}_7$, $\text{Y}_2\text{Si}_2\text{O}_7$, and $\text{Gd}_2\text{Si}_2\text{O}_7$

Material	Zone	O (%)	Ca (%)	Mg (%)	Al (%)	Si (%)	Y (%)	Yb (%)	Lu (%)	Sc (%)	Gd (%)	Phase
$(5\text{RE}_{0.2})_2\text{Si}_2\text{O}_7$	A	49	14	1.2	7.9	26.5	0	0.4	0.5	0	0.5	CMAS
	B	47.2	13.5	0	2.9	28.6	0	1.9	2.2	1.9	1.9	Cyclosilicates
	C	46.7	12.9	0	3.2	28.8	0.7	2.2	2.4	1.2	2.0	Cyclosilicates
	D	52.5	0	0	0	20.9	5.3	5.3	5.4	5.2	5.5	Substrate
	E	57.5	0	0.1	0	41.9	0	0	0.2	0	0.1	SiO_2
	F	45.8	12.4	0	2.9	29.0	0.7	2.1	1.8	1.1	3.2	Cyclosilicates
$\text{Y}_2\text{Si}_2\text{O}_7$	A	55.9	4.9	0.3	1.3	16.8	20.7	—	—	—	—	Apatite
	B	56.8	8.5	0.9	6.9	24.9	1.9	—	—	—	—	CMAS
$\text{Gd}_2\text{Si}_2\text{O}_7$	A	38.2	5.8	6	2.9	31.4	—	—	—	—	15.7	Apatite
	B	42.7	6.2	1.1	11.3	37.6	—	—	—	—	1.2	CMAS

elements from EDS analysis, the dendritic areas were determined to be a $\text{Ca}_3\text{RE}_2(\text{Si}_3\text{O}_9)_2$ cyclosilicate phase, similar to that in the dense reaction-product sublayer.

The cross-sectional morphologies of the corroded $(5\text{RE})_2\text{Si}_2\text{O}_7$ pellets were observed following their exposure to CMAS at 1400 °C for various durations (Fig. 5). The corroded samples exhibited the typical aforementioned three-layer structure, namely a CMAS layer with a precipitation phase on the top, a reaction zone containing the dense Ca–RE–Si cyclosilicate sublayer and the penetration sublayer, and the $(5\text{RE})_2\text{Si}_2\text{O}_7$ substrate. The dense reaction sublayer was initially formed rapidly and further thickened with the prolongation of exposure time at a decreased rate. At an exposure time of ~10 h, the depth of the reaction layer reached ~24 μm. With

further extension of the corrosion time to 20 h, the depth of the reaction layer showed no significant increase (~25 μm). In addition, the dendrite phase appeared in the CMAS region and grew with prolonged exposure time. The penetration sublayer in the reaction zone also slightly increased with increase in the exposure time.

As comparison, the individual RE-disilicates $\gamma\text{-Y}_2\text{Si}_2\text{O}_7$ and $\delta\text{-Gd}_2\text{Si}_2\text{O}_7$ were also corroded by CMAS at 1400 °C for 4 h, and their cross-sectional morphologies were observed (Figs. 4(c) and 4(d)). Unlike $(5\text{RE})_2\text{Si}_2\text{O}_7$, an intense reaction occurred between CMAS and $\text{Y}_2\text{Si}_2\text{O}_7$ or $\text{Gd}_2\text{Si}_2\text{O}_7$ at 1400 °C. The observed regions consisted of CMAS and a reaction product mixture instead of a dense and continuous protective layer. As indicated by EDS and XRD results (Figs. 3(b) and 3(c)), region A in

Fig. 5 (a–e) Cross-sectional SEM images of CMAS-interacted $(5\text{RE}_{0.2})_2\text{Si}_2\text{O}_7$ specimens at 1400 °C for 0, 2, 4, 10, and 20 h, respectively. (a–e) have the same ruler. (f) Depth of dense reactive-product ($\text{Ca}_3\text{RE}_2(\text{Si}_3\text{O}_9)_2$ cyclosilicate) sublayer of $(5\text{RE}_{0.2})_2\text{Si}_2\text{O}_7$ specimens as a function of exposure time in molten CMAS.

Fig. 4(c) and region A in Fig. 4(d) corresponded to the formation of $\text{Ca}_2\text{Y}_8(\text{SiO}_4)_6\text{O}_2$ and $\text{Ca}_2\text{Gd}_8(\text{SiO}_4)_6\text{O}_2$ apatites, respectively; region B in Fig. 4(c) and region B in Fig. 4(d) were attributed to molten CMAS glass with the dissolution of Y or Gd. A small amount of $\text{Y}_3\text{Al}_5\text{O}_{12}$ garnet was also detected during the $\text{Y}_2\text{Si}_2\text{O}_7$ –CMAS interaction (Fig. 3(b)).

4 Discussion

The effect of CMAS corrosion on individual RE-disilicates has been intensively investigated in recent years [11–15]. Two main mechanisms have been shown to account for CMAS corrosion behaviors, depending on the ionic

size of the RE element. CMAS corrosion of disilicates with a small ionic size element such as Sc and Lu [14] is controlled by the penetration of molten CMAS along the grain boundary without the formation of a new phase. Conversely, RE elements with a large ionic size, such as Gd and Y, show a great affinity for Ca in CMAS. Thus, CMAS corrosion of the corresponding disilicates is controlled by the reaction-crystallization process to form apatite phase [5,46,47]. Indeed, the results of CMAS corrosion of $\text{Y}_2\text{Si}_2\text{O}_7$ and $\text{Gd}_2\text{Si}_2\text{O}_7$ herein showed the formation of apatite phases. But the apatite phase presented non-continuous at 4 h. Thus the generated apatite could not reduce the CMAS melt penetration into substrate, thereby losing the capability of protecting CMAS from further damage [12,15]. The

degradation of $\text{Y}_2\text{Si}_2\text{O}_7$ and $\text{Gd}_2\text{Si}_2\text{O}_7$ may be attributed to the weak grain boundary stability at test temperature [15,42].

The multicomponent $(5\text{RE})_2\text{Si}_2\text{O}_7$ material reacted with CMAS very rapidly. Rapid reaction with the CMAS and formation of a dense protective reaction layer could be advantageous for CMAS resistance. The corrosion process could be described as follows: CMAS melts at 1400 °C, and quickly dissolves $(5\text{RE})_2\text{Si}_2\text{O}_7$ and crystallizes from the supersaturated CMAS glass melt to generate Ca–RE–Si cyclosilicates by consuming CaO in CMAS melts, forming a dense protective layer. The thickness of Ca–RE–Si cyclosilicates increased with interaction time increasing (Figs. 5(a)–5(d)). Then, the thickness of reaction-production sublayer remained nearly constant after a period of interaction time (Figs. 5(d)–5(f)). Because the cyclosilicate phase was generated mainly by $(5\text{RE})_2\text{Si}_2\text{O}_7$ interacting with CaO in CMAS melt, the formation of cyclosilicate sublayer would proceed until the residual melt reached equilibrium and the driving force of cyclosilicate formation would be eliminated [13,15]. The Ca:Si ratio dropped monotonically from the initial value of 0.73 (33/45) to 0.53 (14/26.5) at 4 h, until holding a steady value ~ 0.33 (13.7/41.2) at 10 h and ~ 0.31 (13.2/43.1) at 20 h. The similarity of measured Ca : Si ratio of 10 and 20 h most likely suggests that the system is approaching equilibrium. This phenomenon has been demonstrated theoretically and experimentally [13,15,48]. The $(5\text{RE})_2\text{Si}_2\text{O}_7$ also obeys the interaction behavior. Therefore, the reaction sublayer at 10 and 20 h presented the similar thickness. Meanwhile, the excess SiO_2 in this work presented weakness when interacting with molten CMAS. The molten CMAS tended to penetrate along into substrate the excess SiO_2 , accelerating the penetrating and corrosion rate. Therefore, the penetration sublayer was generated in this work and the thickness of penetration sublayer increased at the interacting time increasing.

Similar to most multicomponent compounds [41,44], $(5\text{RE})_2\text{Si}_2\text{O}_7$ shows a single β polymorph phase by the high-entropy effect despite the corresponding individual RE-disilicates having different crystal structures. The five RE elements, with different ionic sizes, randomly occupy the lattice site in $(5\text{RE})_2\text{Si}_2\text{O}_7$, resulting in lattice distortion [44,49]. A severely distorted lattice leads to a fluctuating lattice potential energy for the migration path from one site to another during diffusion [35,50]. As a result, $(5\text{RE})_2\text{Si}_2\text{O}_7$ exhibits slower diffusion and higher activation energy for atomic diffusion than individual

disilicates. Therefore, the interaction of $(5\text{RE})_2\text{Si}_2\text{O}_7$ with CMAS to form a new phase is delayed. In addition, the new phase formed by the interaction of $(5\text{RE})_2\text{Si}_2\text{O}_7$ with CMAS is a cyclosilicate phase composed of five RE elements, including Y, Yb, Sc, Gd, and Lu, rather than an apatite phase. The cyclosilicate is also a multicomponent Ca–RE–Si product. This may account for the formation of a dense reaction layer even at 1400 °C. The existence of such a dense reaction layer could prevent $(5\text{RE})_2\text{Si}_2\text{O}_7$ from further CMAS corrosion. This work is a preliminary observation and understanding on interaction behavior of $(5\text{RE})_2\text{Si}_2\text{O}_7$ with CMAS, and more investigations are still expected to bring to light the kinetics of dissolution and precipitation process in details.

5 Conclusions

Herein, the interaction of a multicomponent RE-disilicate $(5\text{RE})_2\text{Si}_2\text{O}_7$ with molten CMAS at 1400 °C was investigated. The Si to RE molar ratio of 1.15 : 1 was selected to obtain a pure $(5\text{RE})_2\text{Si}_2\text{O}_7$ phase. $(5\text{RE})_2\text{Si}_2\text{O}_7$ showed excellent CMAS resistance. A dense and continuous reaction layer was formed to protect the substrate from rapid dissolution in molten CMAS. Moreover, a sluggish diffusion effect slowed the atomic diffusion, and thereby reduced further corrosion by CMAS. The interaction of $(5\text{RE})_2\text{Si}_2\text{O}_7$ with molten CMAS was controlled by the reaction-recrystallization process. The results of this study reveal that the multicomponent EBC ceramic $(5\text{RE})_2\text{Si}_2\text{O}_7$ shows promise in the development of potential EBC materials.

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