

A matching design between strain tolerance and cracking resistance for a long lifespan in thick thermal barrier coatings

Shuo-Cong Yang^{1,†}, Hai-Lin Yang^{1,†}, Run-Ze Yu^{2,†}, Xue-Ting Jia¹, Itfaq Ali¹, Hussain Sajjad¹, Guang-Rong Li^{1,✉}, Zhi-Yuan Wei³, Guan-Jun Yang^{1,✉}, Yasir Muhammad⁴

Cite this article: Yang S-C, Yang H-L, Yu R-Z, et al. *J Adv Ceram* 2026, **15**(7): 9221332. <https://doi.org/10.26599/JAC.2026.9221332>

ABSTRACT: Failure is a main disadvantage of thermal barrier coatings (TBCs). Typically, whether failure occurs depends on competition between the cracking driving force (negatively related to strain tolerance) and cracking resistance. However, it is difficult to simultaneously enhance these two properties in conventional monostructures since they often need totally opposite structures. In this work, a novel structure was designed to co-enhance strain tolerance and cracking resistance in thick TBCs. The novel structure appears to have trimodal features. The macro-columnar structure was tailored to enhance the strain tolerance, the mesogradient structure in individual columns was porosity-distributed from bottom to top to enhance the cracking resistance, and the microlamellar structure was deposited to further tolerate strain and to prevent heat flux. First, the trimodal-featured structure was tailored in 2000- μm -thick TBCs. Thermal cyclic tests showed that the lifespan was nearly 4 and 9 times that of the conventional one-way designs of columnar and gradient TBCs, respectively. Second, a finite element model was developed to investigate the mechanism responsible for the long lifespan. Cooperation in lowering the driving force and increasing the cracking resistance significantly retards the cracking behavior in thick coatings. Finally, dominant factors of trimodal-featured structures were discussed and optimized to further extend the lifespan of thick TBCs. Overall, the matching design between strain tolerance and cracking resistance provides a fundamental method for durable protection in thick TBCs.

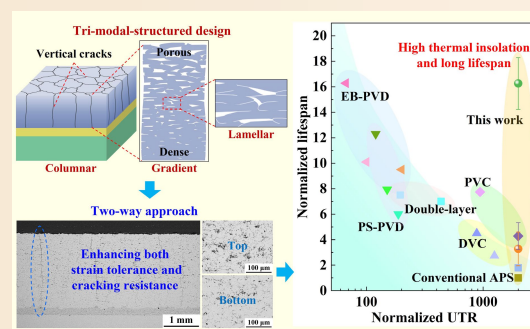
KEYWORDS: thermal barrier coatings (TBCs); matching design; trimodal-featured structure; high thermal insulation; long lifespan

1 Introduction

Thermal barrier coatings (TBCs) are widely used in high-temperature components of land-based gas turbines to protect alloys from direct thermal exposure due to their excellent thermal insulation performance [1–5]. A typical TBC structure has three parts, namely, a nickel-based superalloy substrate, an MCrAlY alloy bond coat (BC), and a thermal insulation ceramic top coat (TC) [6–8]. TBCs need to have the lowest possible thermal conductivity, which is the basis of their thermal insulation ability [9–11]. In addition, to prevent damage to the alloy substrate, the TBC system should also maintain its integrity as long as possible under severe service conditions, avoiding delamination or failure [12,13]. In short, high thermal insulation and long lifespan are the basic performance requirements for TBCs [14,15]. As the service temperature increases, TBCs are required to have higher insulation capability. The demand for a large temperature drop

from the surface to the bottom of TBCs has driven the development of thick TBCs (typically 800–2000 μm thick, used in gas turbine combustors on components such as heat shields and liners) [16–18].

The thermal insulation properties of thick TBCs are significant, but the challenge of thick TBCs is how to ensure their service life [19,20] because the increase in coating thickness leads to an increase in internal stress and thus strain energy, resulting in a significant increase in the cracking driving force. As a result, the coating is more prone to cracking and delamination [19,21]. Strain tolerance (ST) is used to characterize the ability of TBCs to accommodate thermal strain through microstructural deformation, thereby reducing the cracking driving force. The vertical columnar structure, which mitigates thermal stress through intercolumnar debonding and enhances ST, represents a viable strategy to prolong the service life of thick TBCs [22]. Compared with lamellar structure coatings prepared by



† Shuo-Cong Yang, Hai-Lin Yang, and Run-Ze Yu contributed equally to this work.

¹ State Key Laboratory for Mechanical Behavior of Materials, School of Materials Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, China. ² XJTU-POLIMI Joint School, Xi'an Jiaotong University, Xi'an 710049, China. ³ School of Materials Science and Engineering, Hubei University of Automotive Technology, Shiyan 442002, China. ⁴ Department of Materials Science & Engineering, Institute of Space Technology, Islamabad 44000, Islamic Republic of Pakistan.

✉ Corresponding authors. E-mail: G. Li, ligrong@xjtu.edu.cn; G. Yang, ygj@xjtu.edu.cn

Received: February 4, 2026; Revised: April 13, 2026; Accepted: June 4, 2026

© The Author(s) 2026. This is an open access article under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0, <http://creativecommons.org/licenses/by/4.0/>).

conventional atmospheric plasma spraying (APS), dense vertically cracked coatings (DVCs, with a thickness of approximately 500–1500 μm) [22,23] or coatings prepared by electron beam-physical vapor deposition (EB-PVD, with a thickness typically less than 500 μm) [24,25] typically exhibit vertical columnar structures. These structures mitigate the cracking driving force, thereby extending the coatings' service life [22,26]. However, they also have the disadvantage of high thermal conductivity in the vertical direction [27] and a large cracking driving force caused by a high elastic modulus. In addition, bimodal-structured TBCs (with a thickness of approximately 1000 μm) with macroscale vertical cracks and microscale lamellar structures exhibit high thermal insulation and long service life [28,29]. However, the bottom porous lamellar structure has inferior cracking resistance, and the growth stress generated by thermally grown oxide (TGO) and the thermal mismatch stress generated by the difference in the coefficient of thermal expansion between ceramics and metals primarily act on the bottom area of the ceramic TC during service [30–32]. These factors pose critical risks of coating failure, especially for thicker coatings. Overall, when the coating thickness is greater (e.g., 2000 μm in this work), for coatings with a monolayer structure along the thickness direction, neither lamellar porous structures (with poor cracking resistance at the bottom) nor dense structures (with high elastic modulus and thus large cracking driving force) can simultaneously satisfy the requirements for excellent thermal insulation and long service life of thick TBCs.

To address the above problem, a nonuniform structural design along the coating thickness direction is an effective approach for achieving excellent thermal insulation and prolonged service life, especially for thick coatings where more design freedom is available along the thickness dimension. Two typical examples of nonuniform structures are the gradient pore structure design of the same material [33–35] and the double-layer (or multilayer) structure design of dissimilar materials [36–39]. The advantage of this nonuniform structure is the synergistic optimization of the thermal insulation and service life of the coating via the toughening of the bottom layer and the heat resistance of the top layer [33,38,40,41]. Combining columnar structures with nonuniform structures may be a strategy to further enhance the performance of thick TBCs. Nevertheless, a key challenge in implementing nonuniform structures along the thickness direction of thick coatings is how to controllably generate vertical cracks within the coating. Previous studies confirmed that two key parameters are the ratio of vertical crack depth to coating

thickness and the crack density, and that a sufficiently large ratio (which should exceed 0.5) and sufficiently small crack spacing usually indicate a longer service life [21,26,42]. The conventional method for forming vertical cracks is to induce cracks from the surface to the bottom [28]. However, when applied to thick nonuniform structures, due to the relatively small cracking driving force in the vertical direction [43], this conventional method fails to make vertical cracks continue to propagate to the bottom and even propagate laterally at the interface between porous and dense regions, resulting in delamination and spallation.

In this work, thick TBCs with trimodal-structured characteristics of macro-columnar structure, mesogradient structure, and microlamellar structure were designed to enhance both the thermal insulation and lifespan. A vertical crack formation method from the inside out was developed to generate vertical cracks with a large depth in the gradient lamellar structured coating. Then, thermal cycling experiments were carried out to compare the lifespan of different samples, and the failure mechanism was deduced from the changes in coating structure before and after failure. This design can maintain the high thermal insulation ability of TBCs while prolonging the coating lifespan, which provides a possibility for the development of advanced TBCs.

2 Experimental

2.1 Design of trimodal-structured TBCs

In previous studies, the service life of TBCs was typically extended using a one-way method by enhancing either ST or cracking resistance. For example, this method introduced a columnar structure into coatings to enhance ST [28] or a gradient structure to enhance cracking resistance [33]. To better meet the requirement of long service life, this study proposes a trimodal-structured TBC design by adopting a two-way approach that enhances both ST and cracking resistance. As shown in Fig. 1, the TBC shows the characteristics of macro-columnar structure, mesogradient structure, and microlamellar structure. At the macroscale, the ceramic TC is divided into many columns by vertical cracks that are connected into a network to tolerate the strain caused by the thermal expansion mismatch between the substrate and the coating. At the mesoscale, in each column, the ceramic TC gradually transitions from the dense bottom to the porous top, showing a gradient structure to consider the cracking resistance of the bottom and the thermal insulation of the top. In

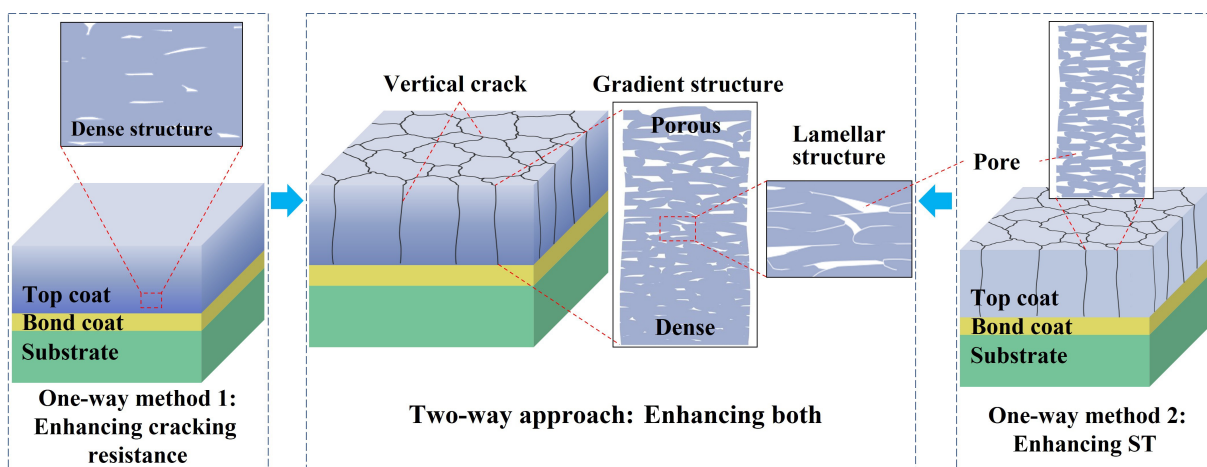


Fig. 1 Design of a trimodal-structured TBC with macro-columnar, mesogradient, and microlamellar features in thick top coat.

addition, at the microscale, the coating is stacked by many splats, and there are pores between splats, which is the reason for the low thermal conductivity of the coating.

2.2 Preparation of TBCs

Before depositing the ceramic coating, the commercially available NiCoCrAlTaY powders (Amdry 997) were deposited on the nickel-based superalloy substrate by high-velocity oxygen fuel to form a BC, and the target thickness was 200 μm . The substrate is Inconel 738 alloy with a size of 25.4 mm in diameter and 5 mm in thickness. Before depositing the ceramic TC, the BC was subjected to a preheating treatment [44,45]. The preheating treatment was conducted in a furnace with precisely controlled oxygen partial pressure (PCO-1200A, Xi'an Jiaotong University, China), and it was first carried out at 1000 $^{\circ}\text{C}$ for 4 h with an oxygen partial pressure of 0.01 ppm and then at 1080 $^{\circ}\text{C}$ for 4 h with an oxygen partial pressure of 10 ppm in an Ar atmosphere. This two-step treatment was designed to promote the agglomeration of the as-deposited amorphous Al_2O_3 film into discrete particles, thereby exposing the underlying metallic phases and enabling the formation of a uniform and compact $\alpha\text{-Al}_2\text{O}_3$ film with a larger grain size during subsequent oxidation, which effectively reduces the TGO growth rate and enhances the oxidation resistance of BC [45].

The ceramic TC is deposited by APS using commercially available yttria-stabilized zirconia (YSZ) hollow spherical powders (Metco 204B-NS and 204NS-G), with a total thickness of approximately 2000 μm . The morphology and particle size distribution of the powders are shown in Fig. 2. The dense bottom region was deposited with small powders (sieved 204NS-G, a size distribution ranging from 20 to 49 μm), with a thickness of approximately 500 μm . The middle transition region was deposited with large powders (sieved 204B-NS, a size distribution

ranging from 38 to 87 μm), with a thickness of approximately 500 μm . The porous top region was deposited with the same powders as the middle region, with a thickness of approximately 1000 μm . The APS parameters for the top coat are shown in Table 1. During the spraying process, the thickness of each layer was determined by a micrometer. In addition, uniform lamellar porous structure coatings with and without vertical cracks were also prepared for comparison.

2.3 Preparation of vertical cracks in a gradient structure

In this study, two methods were used to form vertical cracks, including the conventional method and the improved method. For the conventional method [28], after the ceramic TC is deposited, the vertical cracks propagate from the surface of the coating to the inside through heating of the substrate side and rapid cooling of the coating side. However, for thick coatings with gradient structures, vertical cracks have difficulty extending to the deeper part of the bottom region of the coating by this conventional method. Therefore, this study proposes an improved method to generate vertical cracks. As shown in Fig. 3, vertical cracks are formed by layer-by-layer deposition and layer-by-layer cooling. The coating is composed of many stacked splats. During the coating deposition process, each cooled splat produces small cracks along the vertical direction due to volume shrinkage and constraints. After layer-by-layer deposition, the substrate side is heated to impose a constraint, and a high-pressure cold air jet is used for rapid cooling. During the cooling process, there is a large temperature gradient along the vertical direction. Compared with the lower layer, the upper solidified layer has greater volume shrinkage and is also subjected to greater tensile stress, which makes the pores in the coating and the small cracks in the splats interconnected in the vertical direction, resulting in macroscale vertical cracks. After cooling, deposition of the coating continues. The preexisting vertical cracks act as crack sources and continue to propagate upward during the subsequent cooling process until they reach the coating surface. The parameters for forming vertical cracks are shown in Table 2.

2.4 Experimental group design

A total of five groups of samples were prepared in this work. To serve as a control group that enhanced only cracking resistance, the first group consisted of TBCs with a gradient pore structure (without vertical cracks). They were fabricated by adjusting the APS parameters and were designated Grad-No-VCs. To serve as a control group that enhanced only ST, the second group consisted of columnar/lamellar bimodal-structured TBCs. They were fabricated by introducing vertical cracks into a uniform lamellar porous structure using the conventional method and were designated Porous-VCs (PVC). Subsequently, based on the gradient structure, vertical cracks were introduced into the TBCs using a conventional method to form gradient columnar TBCs,

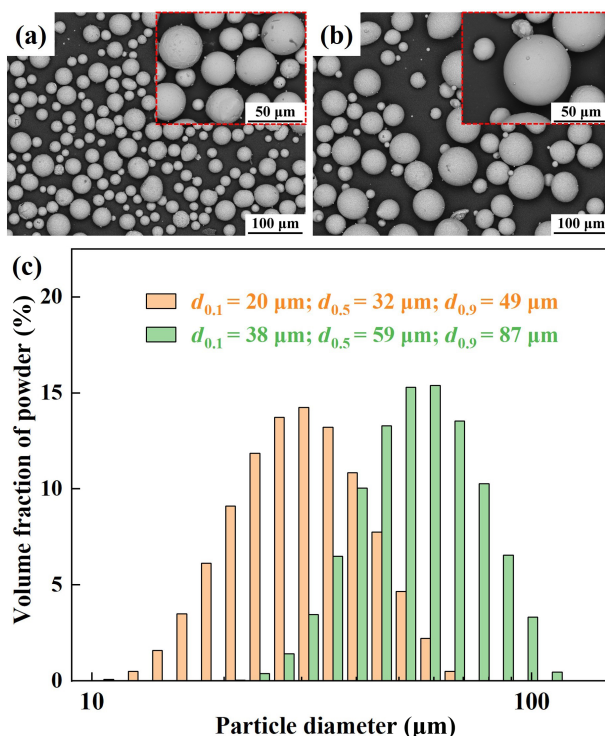


Fig. 2 Powders for deposition of top coat: (a) small powders, (b) large powders, and (c) powder size distribution. Note: $d_{0.1}$ represents that 10% of the total particle volume is smaller than this particle size, and $d_{0.5}$ and $d_{0.9}$ follow the same logic by corresponding to 50% and 90% volume fractions respectively.

Table 1 APS parameters

Parameter	Top	Middle	Bottom
Arc current (A)	600	600	600
Arc voltage (V)	70	70	70
Plasma gas (Ar) flow ($\text{L}\cdot\text{min}^{-1}$)	45	45	45
Plasma gas (H_2) flow ($\text{L}\cdot\text{min}^{-1}$)	7	7	7
Powder feed rate ($\text{g}\cdot\text{min}^{-1}$)	30	30	30
Spray distance (mm)	100	80	80
Torch traverse speed ($\text{mm}\cdot\text{s}^{-1}$)	500	400	400
Preheating temperature ($^{\circ}\text{C}$)	—	300	600

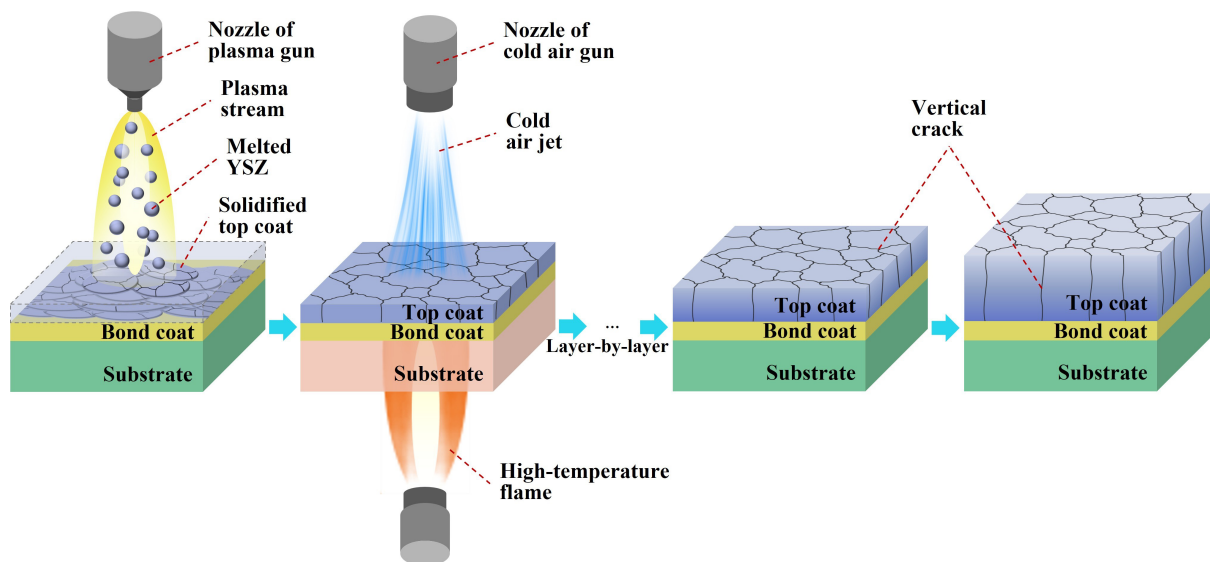


Fig. 3 Schematic of forming vertical cracks from bottom layer to top layer.

Table 2 Parameters for forming vertical cracks

Parameter	Value
Heating temperature (°C)	600
Cold air jet pressure (MPa)	0.73
Nozzle-to-surface distance (mm)	30
Duration (s)	20

which were designated Grad-Short-VCs. As the experimental group, gradient columnar TBCs that enhance both ST and cracking resistance via a two-way approach were prepared using a layer-by-layer deposition and cooling process, where vertical cracks formed from the inside out; these TBCs were designated Grad-VCs. Additionally, uniform lamellar porous TBCs without vertical cracks were prepared as an extra control group and designated Porous-No-VCs.

2.5 Characterization of microstructure and properties

The microstructural changes of the coating before and after failure were observed by a scanning electron microscope (SEM; TESCAN MIRA 3, The Czech Republic). Using ImageJ software, the changes in pore parameters in different regions of the gradient-structured coating were measured from 10 SEM images. The porosity was characterized by the total area of pores per unit area, and the two-dimensional (2D) pore density (μm^{-2}) was characterized by the total length of 2D pores per unit area. The relevant details of the quasi-*in-situ* observation can be found in our previous study [46].

Hardness (Vickers hardness, HV) and elastic modulus were determined by a microindentation hardness tester (Buehler-MicroMet 5104, Akashi Co., Japan). The load of the indentation test was 300 gf, and the holding time was 30 s. At this load, the measured hardness and elastic modulus represent the overall behavior of the porous matrix, allowing the average mechanical properties to be evaluated within an acceptable margin of error.

Independent single-layer samples of the top, middle, and bottom regions were sprayed separately under the same conditions for thermal conductivity measurement. The thermal diffusivity was measured by a laser flash apparatus (LFA 457, Netzsch, Germany). The specific heat capacity was measured by a differential scanning calorimeter (DSC404, Netzsch, Germany). The density was calculated by measuring the dimensions and

mass of the coating sample. Thermal conductivity (λ) is determined by Eq. (1):

$$\lambda = \alpha \cdot c_p \cdot \rho \quad (1)$$

where α is the thermal diffusivity; c_p is the specific heat capacity; ρ is the density.

2.6 Thermal cycling test

An isothermal thermal cyclic test at 1050 °C was used to evaluate the lifespan of the TBCs, and each cycle included heating, holding for 50 min, and air cooling for 10 min. A sample is deemed to fail if the area of delamination or spallation exceeds 50% of its total area. At least two samples were tested per group.

3 Finite element simulation

3.1 Model geometry and boundary conditions

ABAQUS finite element analysis software was employed to model the thick gradient TBCs. The coating system consists of a substrate (SUB), a BC, a TGO, and three layers (top, middle, and bottom) of the TC. The total thickness of the TC is 2000 μm , while the BC and substrate have thicknesses of 200 μm and 1 mm, respectively. The TGO thickness increases with oxidation time. All materials in the model were assumed to be isotropic and homogeneous to simplify the model and highlight the influence of structural characteristics. While this simplification may affect the absolute values, the relative trends and mechanisms remain valid. The meshing strategy refined the crack-prone interface regions using a finer grid density while employing coarser elements near the top of the ceramic layer and the base of the substrate. As shown in Fig. 4(a), the influence of vertical crack spacing on stress and crack propagation during the service of coatings was investigated. The bottom of the model and the right side of both the BC and the substrate were constrained, while a 0.3% strain ($\Delta\alpha \cdot \Delta T$, where $\Delta\alpha$ and ΔT represent the difference in thermal expansion coefficient and the temperature change, respectively) was applied to the left side of the model to simulate thermal mismatch strain in TBCs caused by differential thermal expansion between layers during thermal cycling. Periodic boundary conditions were adopted to reduce computational costs [47]. Due to the symmetry about the central axis, only half of the periodic unit was modeled to further

simplify the simulation. A preexisting horizontal crack (20 μm in length) was embedded within the ceramic TC 20 μm above the BC interface to simulate the location where cracking and spalling are most likely to occur during the actual service of the coating. Furthermore, two finite element models corresponding to distinct vertical crack formation methods were established in this study, as shown in Fig. 4(b). These models analyzed how different vertical crack formation methods govern stress and crack propagation evolution at both vertical and horizontal crack tips. Horizontal cracks were embedded bilaterally at the vertical crack tip to simulate the interaction between propagating vertical cracks and preexisting horizontal pores within the lamellar coating. In addition, the variation in the cracking driving force caused by structural changes in the TBCs during thermal cycling was also simulated, and the model is shown in Fig. 4(c).

3.2 Cyclic thermal loading and stiffening effect

The thermal cycling process of TBCs was simulated, with each cycle consisting of a heating stage, a holding stage, and a cooling stage. During the holding stage, the stiffening of the TBC and thickening of the TGO occurred simultaneously. A subroutine was developed to control this process, and the relevant details can be found elsewhere [47].

3.3 Crack propagation

The strain energy release rate (SERR) represents the energy released by the system during crack propagation and acts as the

fundamental driving force for crack advancement within TBCs. The SERR was calculated by the virtual crack closure technique (VCCT) [48].

4 Results

4.1 Structure of TBCs

Figure 5 compares the macrostructure of the different TBCs, including Porous-No-VCs (conventional control group), Grad-No-VCs (control group that enhanced only cracking resistance), Porous-VCs (control group that enhanced only ST), Grad-Short-VCs, and Grad-VCs (two-way approach that enhances both ST and cracking resistance). Figure 5(a) shows the schematic diagram and cross-sectional morphology of different TBCs. All TBCs have very similar thicknesses, which are approximately $2000 \pm 100 \mu\text{m}$. Figures 5(b) and 5(c) show the vertical crack spacing and the ratio of crack depth to coating thickness of different TBCs, respectively. Compared with Grad-Short-VCs, Grad-VCs have significantly smaller crack spacing, and the ratio of crack depth to coating thickness is also significantly higher than that of Grad-Short-VCs. In addition, Grad-VCs and Porous-VCs both all have smaller crack spacings and larger crack depths than Grad-Short-VCs. Among them, the crack spacing of Grad-VCs is slightly smaller than that of Porous-VCs, and the crack depth is slightly larger than that of Porous-VCs, but this difference is not pronounced.

Figure 6 presents the changes in the structure and pore

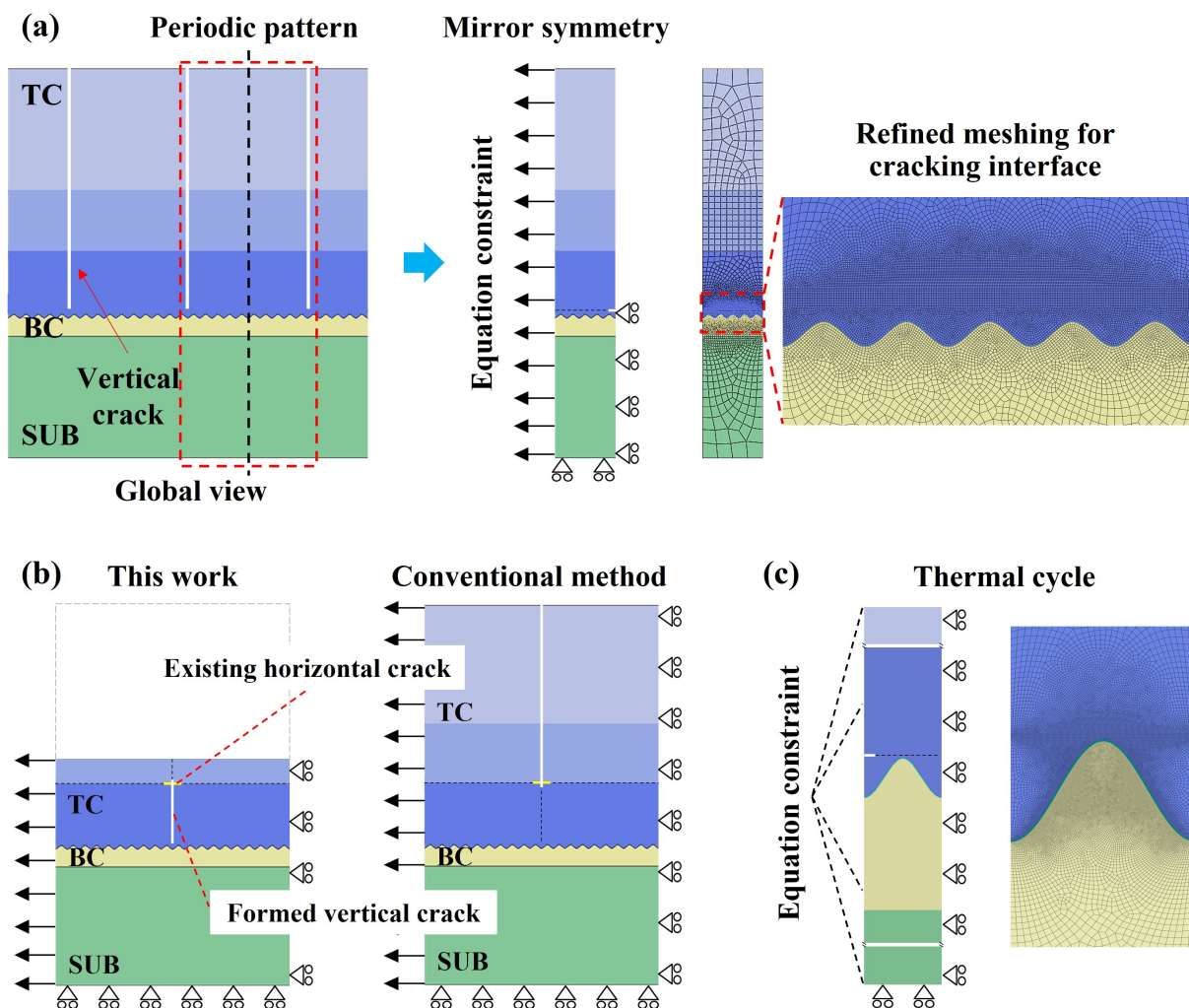


Fig. 4 Development of model in ABAQUS: (a) TBC with vertical cracks, (b) distinct vertical crack formation methods, and (c) thermal cycle.

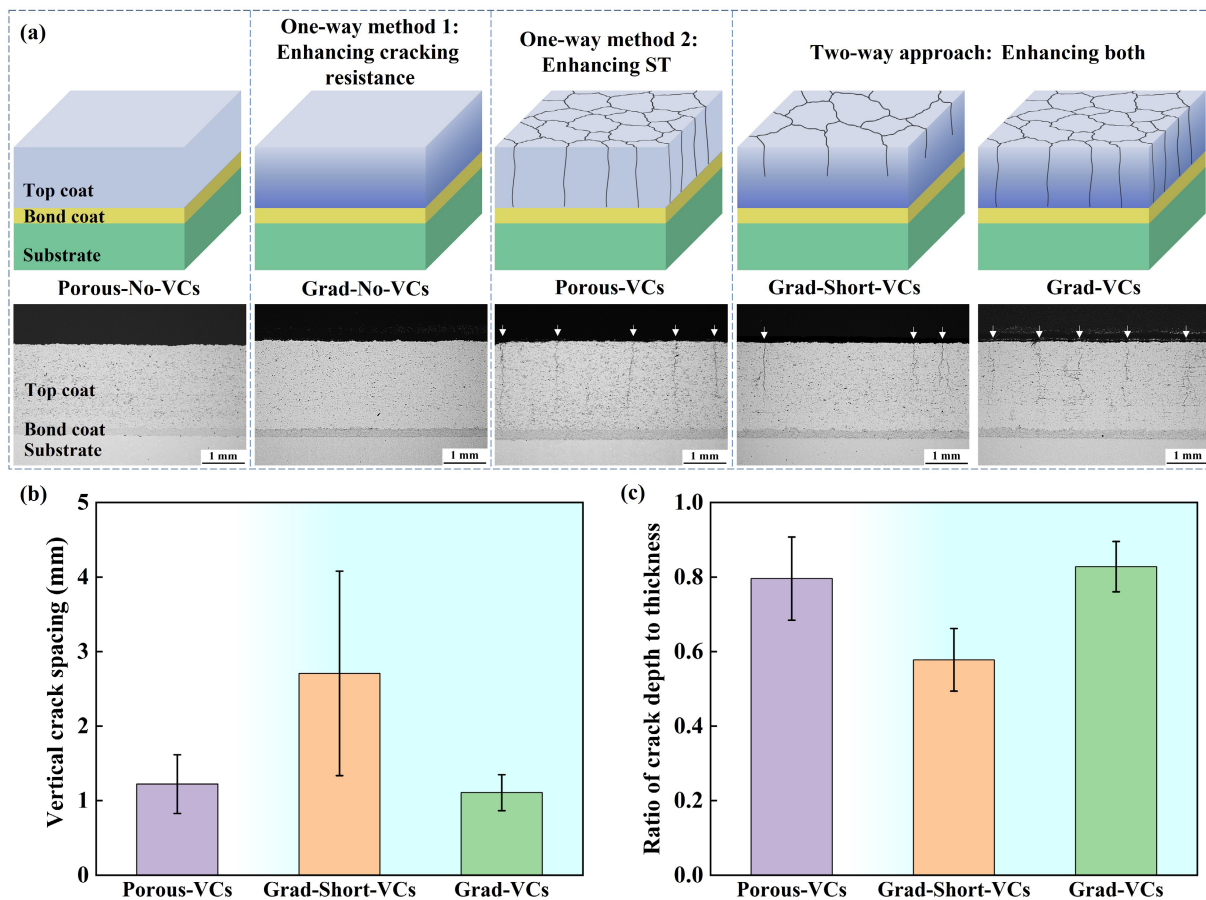


Fig. 5 Structures of different TBCs: (a) structural schematic and cross-sectional morphology, (b) comparison of vertical crack spacing, and (c) ratio of crack depth to coating thickness.

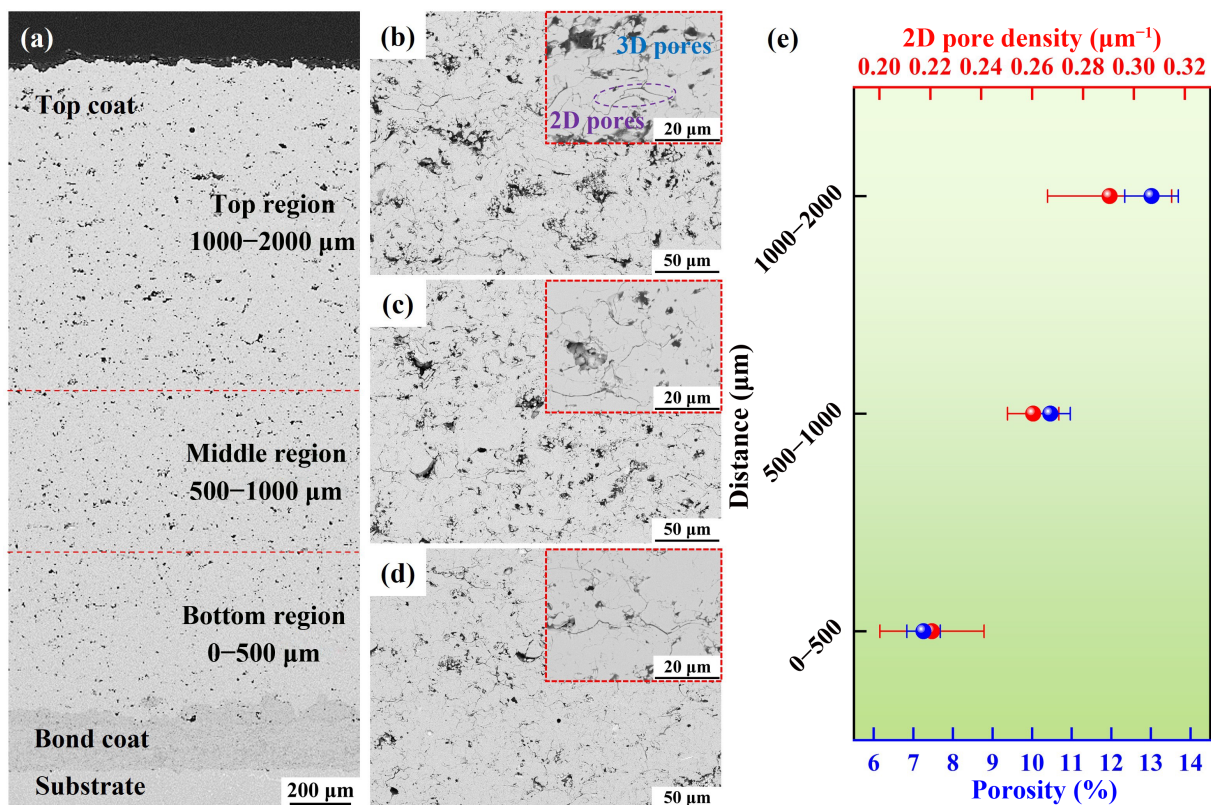


Fig. 6 Change of microstructure, porosity, and 2D pore density of gradient-structured coating: (a) overall cross-sectional morphology, (b) top region, (c) middle region, (d) bottom region, and (e) porosity and 2D pore density at different distances.

parameters of the polished cross-section of the sample with a gradient structure, where Fig. 6(a) shows the macromorphology of the coating, and Figs. 6(b)–6(d) display the micromorphologies of the top, middle, and bottom regions of the ceramic TC, respectively. In the gradient structure, different structures can be observed in different regions from the bottom to the top of the coating. In the bottom region, due to the high melting degree of powders, the splats exhibit tight bonding, resulting in a dense structure with a porosity of approximately $7.3\% \pm 0.4\%$ and a 2D pore density of approximately $0.22 \pm 0.02 \mu\text{m}^{-1}$. At the same time, in the top region, the coating exhibits significant changes, with more pores. Its porosity is approximately $13.0\% \pm 0.7\%$ and the 2D pore density is approximately $0.29 \pm 0.02 \mu\text{m}^{-1}$. In general, there is an increasing number of pores from the bottom to the top, and the coating shows a mesoscale gradient structure and a microscale lamellar structure.

4.2 Thermal insulation capability of TBCs

In previous research, unit thermal resistance (UTR) was used to evaluate the thermal insulation performance of TBCs, as shown in Eq. (2) [38,49]:

$$\text{UTR} = \frac{\delta}{\lambda} \quad (2)$$

where δ is the thickness of the coating and λ is the thermal conductivity.

In this work, porous YSZ is used for the top layer, and dense YSZ is used for the bottom layer. For gradient-structured TBCs, the total UTR is the sum of the UTRs of each layer. Because the interfaces between adjacent layers in the pore-graded coating bond well and involve only a continuous variation in pore characteristics, the contribution of interfacial thermal resistance is considered negligible. Therefore, the UTR of gradient TBCs can be expressed as Eq. (3):

$$\text{UTR} = \frac{\delta_{\text{top}}}{\lambda_{\text{top}}} + \frac{\delta_{\text{middle}}}{\lambda_{\text{middle}}} + \frac{\delta_{\text{bottom}}}{\lambda_{\text{bottom}}} \quad (3)$$

where δ_{top} , δ_{middle} , and δ_{bottom} are the thicknesses of the top, middle, and bottom regions, respectively. λ_{top} , λ_{middle} , and λ_{bottom} are the thermal conductivities of the top, middle, and bottom regions, respectively.

The thermal conductivities of the top, middle, and bottom regions of the gradient-structured coating in this work are 0.9, 1.0, and $1.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, respectively, measured at 1000°C . The thermal conductivity of the conventional lamellar porous structure coating is the same as that of the middle region of the coating. The thicknesses of the top, middle, and bottom layers of the gradient-structured coating are 1000, 500, and $500 \mu\text{m}$, respectively, with a total thickness of $2000 \mu\text{m}$, and these thicknesses were determined based on the total thickness and the requirement that the overall UTR be comparable to that of conventional lamellar porous coatings. The introduction of vertical cracks has only a minor effect on thermal insulation [28] because the cracks are very narrow and oriented parallel to the heat flow direction. When the thickness is the same as that of TBCs in this work, the normalized UTR and thermal conductivity of several typical columnar-structured TBCs (plasma spraying (PS)-PVD [50], EB-PVD [51], and DVC [52]) are shown in Fig. 7, where blue dots represent thermal conductivity and bars represent normalized UTR. The gradient TBC designed in this study exhibits thermal insulation performance similar to that of conventional lamellar porous coatings, while its thermal insulation performance is superior to that of coatings with other structures.

4.3 Thermal cyclic lifespan

Figure 8 shows the lifespans of thick TBCs with different structures after the thermal cyclic test. Conventional lamellar Porous-No-VCs showed the shortest lifespan. In contrast, Grad-No-VCs (enhancing only cracking resistance) and Porous-VCs (enhancing only ST) exhibited lifespans approximately twice and four times that of Porous-No-VCs, respectively. The average lifespan of Grad-Short-VCs was nearly three times that of Porous-No-VCs. With an increased ratio of crack depth to thickness and decreased crack spacing, Grad-VCs exhibited a lifespan of 634 cycles, approximately 16 times that of Porous-No-VCs, which demonstrates that the vertical crack spacing and propagation depth have significant effects on the lifespan of TBCs.

4.4 Failure modes

Figure 9 shows the cross-sections of different failed TBCs. For Porous-No-VCs and Grad-No-VCs, transverse cracks causing cracking failure appear inside the ceramic TC, and the coating shows the characteristics of local spalling. For Grad-Short-VCs with large vertical crack spacing and small crack depth, these coatings still present the failure form of local spalling. The residual ceramic coating is divided into discontinuous parts by vertical cracks, and there is a V-shaped boundary between the two adjacent parts. This is an interesting phenomenon because the crack depth of the original coating is only approximately half of the coating thickness. On the one hand, this means that during

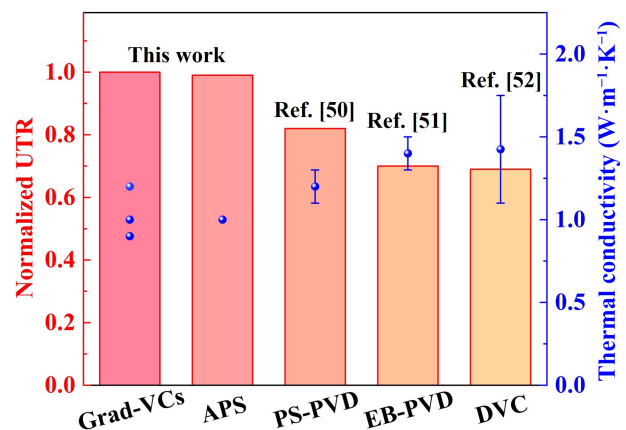


Fig. 7 Thermal insulation performance of different TBCs.

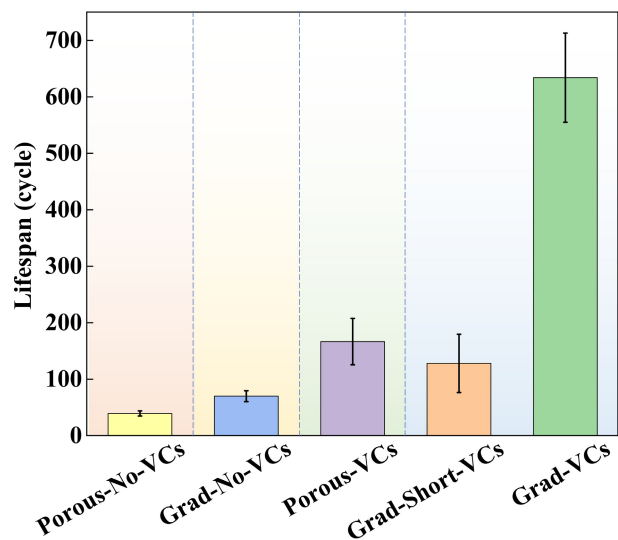


Fig. 8 Thermal cyclic lifespans of different TBCs.

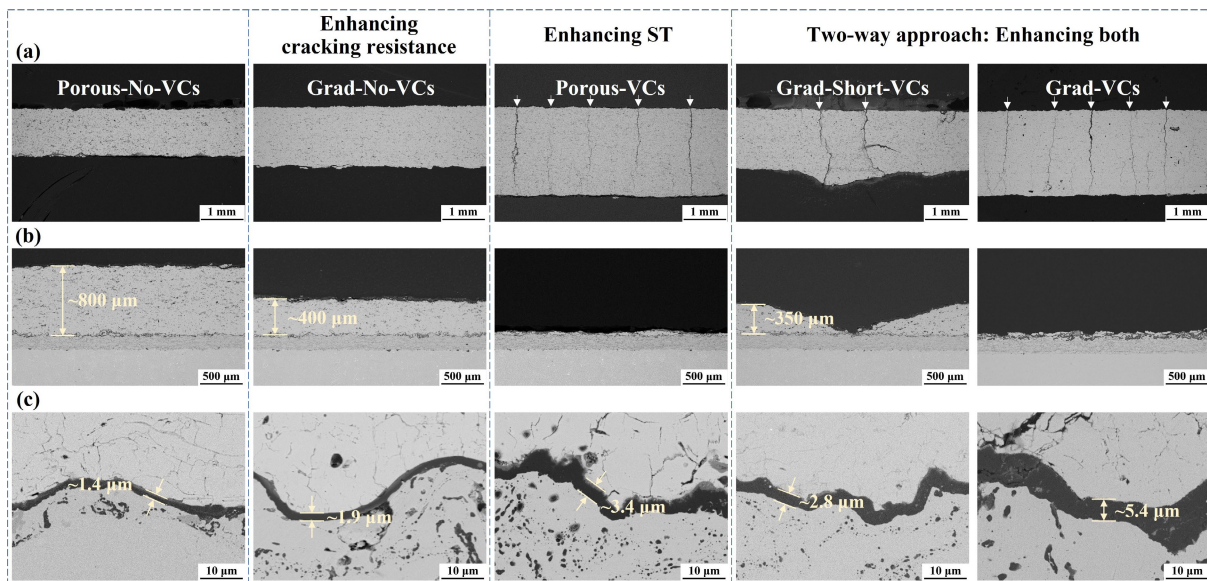


Fig. 9 Cross-sections of failed TBCs: (a) cross-sectional morphologies of ceramic top coats, (b) macroscopic cross-sectional morphologies, and (c) microscopic cross-sectional morphologies.

the thermal cycle, the vertical cracks continue to expand downward to relieve the stress in the coating. On the other hand, the existence of vertical cracks causes the direction of transverse crack propagation to tilt. A notable fact is that when the vertical crack spacing is large and the depth is small, the failure mode of the coating has the characteristics of local spalling, while when the crack spacing is small and the crack depth is large, the failure mode gradually changes. For example, Grad-VCs and Porous-VCs have similar failure morphologies, and horizontal cracks appear near the BC, showing the characteristics of overall peeling off of the coating. Because the surface of the BC is relatively rough, some parts of the TC remain attached. In addition, all coatings formed a continuous TGO on the surface of BC, and the thickness of TGO increased with increasing thermal cycle lifespan.

5 Discussion

5.1 Formation method of vertical cracks

Different vertical crack preparation methods contribute differently to the formation of vertical cracks. A comparison between the improved vertical crack preparation method in this study and the conventional method is shown in Fig. 10. It can be observed that for the improved method in this work, during the propagation of the vertical crack, when the propagating vertical crack tip encounters preexisting horizontal pores (20 μm in length), the normal stress at the vertical crack tip (σ_{yy}) is 126 MPa; the normal stress at the horizontal crack tip is 86 MPa. Both the normal stress and SERR at the vertical crack tip are greater than those at the horizontal crack tip, which indicates that the crack is more likely to continue propagating in the vertical direction. In contrast, for the conventional method, the horizontal crack tip has higher normal stress and SERR than the vertical crack tip, suggesting that under this condition, the crack tends to propagate transversely, which is unfavorable for the formation of vertical cracks. The influence of the length of preexisting horizontal pores on the SERR for different cracking directions was further investigated, as shown in Figs. 10(b1) and 10(b2). As the horizontal pore length increases, the SERR at the horizontal crack tip first increases and then tends to stabilize; in contrast, the SERR at the vertical crack tip gradually decreases and eventually becomes lower than that at

the horizontal crack tip. For the method of forming vertical cracks from the inside-out method, the SERR of vertical cracks is greater than that of horizontal cracks over a relatively large range (with horizontal crack lengths of approximately 2–40 μm). However, for the conventional method, this range is very small (approximately 2–15 μm), making it inevitable that the lengths of some 2D pores will exceed this range. The inside-out method of forming vertical cracks significantly increases the SERR in the vertical cracks while effectively reducing it in the horizontal cracks. This keeps the vertical SERR higher than the horizontal SERR over a wider range, which is more favorable for crack propagation along the vertical direction. Figures 10(c1) and 10(c2) illustrate the limitation of vertical crack formation via the conventional method: As vertical cracks propagate downward, they may change direction, leading to the generation of transverse cracks and even layer delamination in the TBCs. Moreover, vertical cracks begin to form on the surface only after the entire coating has been fully deposited. The gradient structure and the lamellar porous structure in the top region relieve stress, resulting in fewer vertical cracks. In contrast, for the inside-out method of forming vertical cracks, vertical cracks first form in the dense bottom region during the initial deposition stage. As spraying continues, the preexisting vertical cracks act as crack sources, promoting further crack propagation during the layer-by-layer deposition and cooling process until the cracks extend to the entire top of the coating. This process accounts for the considerable crack depth and density achieved by the inside-out method. Therefore, the superior preparation method is the reason for the longer vertical cracks and smaller vertical crack spacing in the TBCs. In the as-sprayed state, deeper vertical cracks and smaller vertical crack spacing in the coating provide higher ST, thereby enabling the coating to exhibit an extended lifespan.

5.2 Failure mechanism

5.2.1 Failure mechanism caused by the growth of TGO

During the high-temperature service of TBCs, BC undergoes oxidation. The equivalent thermal exposure time was calculated based on the thermal cycle lifespan of the samples, and the TGO thicknesses of different failed samples were statistically

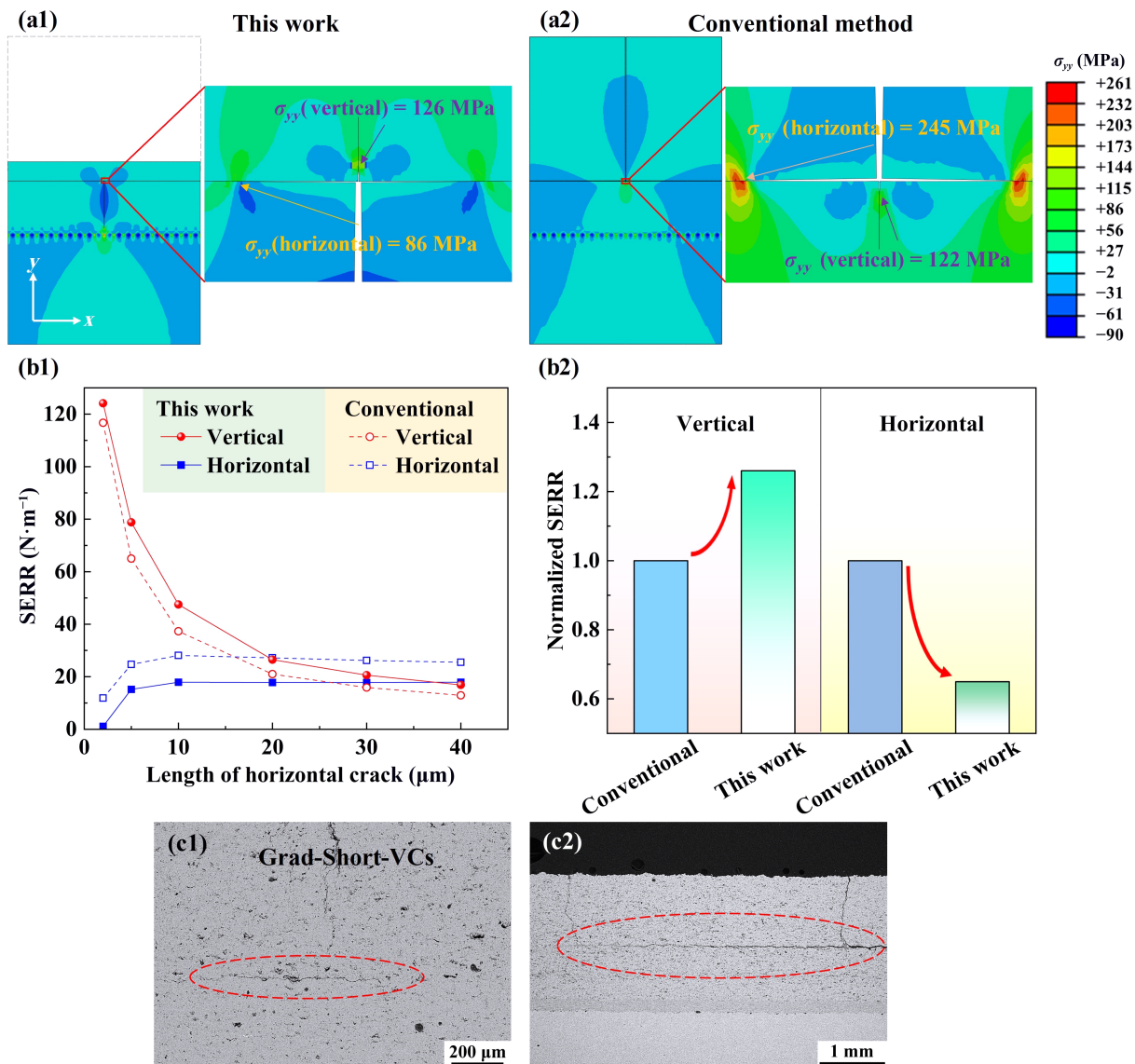


Fig. 10 Effects of different vertical crack preparation methods: (a1, a2) normal stress, (b1, b2) SERR, and (c1, c2) horizontal cracking and delamination caused by conventional method.

analyzed, as shown in Fig. 11. The scatter points show a good fit with the fitted line, indicating that the TGO thickness has an approximately parabolic relationship with oxidation time. In the early stage of service, the TGO grows rapidly; as the TGO thickens, its growth rate gradually slows. Grad-VCs have the longest thermal cycle lifespan, and the failure TGO thickness is also the largest, averaging approximately 6.6 ± 1.3 μm , which exceeds the critical TGO thickness (approximately 5–6 μm) [30,53].

In the cross-sectional morphology of the TGO in the failed Grad-VCs, it is found that, in addition to the white YSZ phase, the metallic BC phase, and the black TGO, there is also a gray-contrast phase on the side of the TGO close to the ceramic TC, as shown in Fig. 12(a). The energy-dispersive spectroscopy elemental mapping is shown in Fig. 12(b). The results indicate that the gray-contrast phase is mainly composed of mixed oxides of elements such as Ni and Cr. As the Al in BC is continuously consumed, it becomes difficult to continue forming a uniform and dense α - Al_2O_3 TGO [54,55]. Meanwhile, mixed oxides grow rapidly, leading to a continuous increase in internal stress within the coating, which can easily cause the coating to crack [56–58].

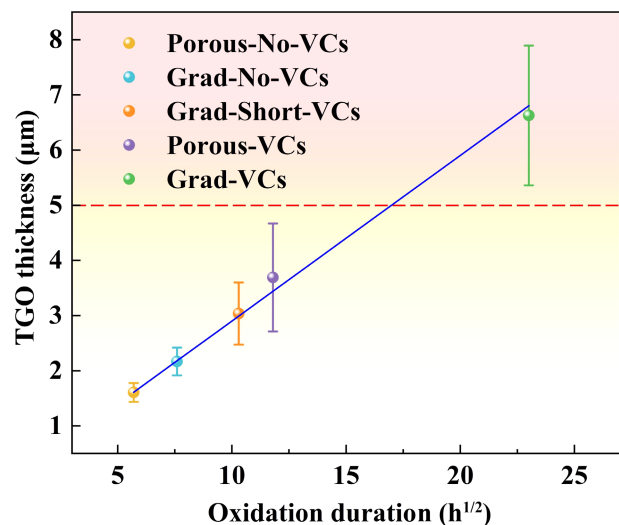


Fig. 11 Oxidation kinetics curve of TGO.

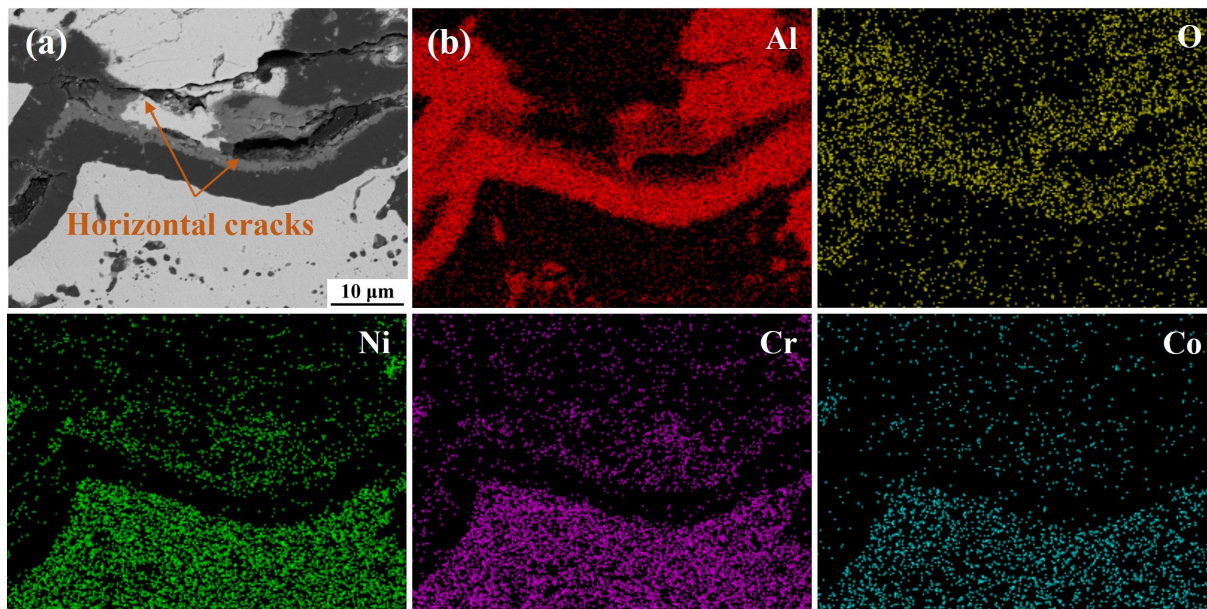


Fig. 12 (a) TGO morphology and (b) elemental distribution.

Therefore, the oxidative thickening of TGO is one of the main causes for the failure of TBCs in this study.

5.2.2 Failure mechanism caused by decreases in ST

During the cyclic service process of TBCs between high and low temperatures, they need to withstand the thermal mismatch strain caused by the difference in thermal expansion coefficients between the ceramic TC and the metal substrate. The porous lamellar structure of plasma-sprayed TBCs can withstand such strain relatively well. However, due to the sintering effect at high temperatures, the microstructure of the ceramic TC gradually changes over time, leading to performance degradation and ultimately to coating failure. Therefore, attention should first be paid to the changes in the morphological structure of the coating during thermal exposure. Figure 13 shows the morphological changes of the gradient coating after exposure to a high-temperature environment of 1300 °C for different durations. With the extension of sintering time, shrinkage and reduction of the pore structure can be observed in all three regions of the gradient coating. The 2D pore lines gradually become shorter or even disappear, leaving only some spherical pores, and the overall structure of the coating tends to be significantly denser.

Observing TBCs at a finer microscopic scale can explain this change, as shown in Fig. 14. The as-sprayed splats are composed of numerous columnar grains with smooth and flat surfaces. Due to limited bonding, there are 2D pores distributed between the splats, which are wide in the middle and narrow around the edges. After thermal exposure, the surfaces of the splats gradually change from relatively smooth to rough and undulating, and the grains gradually merge and grow. As the thermal exposure time is prolonged, the raised grains on the rough upper and lower surfaces of some 2D pores gradually approach or even come into contact with each other, causing long 2D pores to be divided into several short parts. This contact eventually leads to the healing of some 2D pores.

Changes in the microstructure induce changes in its mechanical properties. The variation of the pore structure parameters and mechanical properties of the gradient TBCs with thermal exposure time at 1300 °C are shown in Fig. 15. As the thermal exposure time is prolonged, the porosity and 2D pore

density first decrease rapidly, then the decrease gradually slows, and the values tend to stabilize, showing a two-stage characteristic with two different rates of change. In contrast to the changes in pore structure, both the hardness and elastic modulus of the coating increase. The increase is significant within 20 h and then becomes slight after 20 h, showing a two-stage characteristic similar to that of the pore structure.

The as-sprayed plasma-sprayed TBCs have a high ST, which benefits from their typical porous lamellar structure. However, after thermal exposure, the service performance of the TBCs deteriorates due to inevitable structural densification. Therefore, it is necessary to explore in detail the correlation between the structural and performance changes of the coating. The stiffening degree is used to characterize the change in elastic modulus after thermal exposure relative to the as-sprayed state, and its relationship to the degrees of change in the coating's hardness, 2D pore density, and porosity is established, as shown in Figs. 16(a1) and 16(a2). It can be observed that the degrees of change in the coating's 2D pore density, hardness, and elastic modulus are relatively close, while the degree of change in porosity is significantly smaller. Specifically, the degrees of change in 2D pore density, hardness, and elastic modulus in the three different regions of the gradient TBCs all exceed 60%, while the degree of change in porosity in the bottom region of the coating does not exceed 30% and those in the top and middle regions are only approximately 20%.

Due to the inevitable thermal mismatch strain during the service of TBCs, the coatings are required to exhibit ST. ST is one of the key performance indicators for the service of TBCs, and its level directly affects the lifespan of TBCs. ST can be approximately characterized by the reciprocal of the elastic modulus ($1/E$) [28]. Further statistical analysis was conducted on the variations of 2D pore density and porosity with normalized ST in different regions of the gradient TBC, as shown in Figs. 16(b1) and 16(b2). When the 2D pore density is zero, the porosity remains a nonzero positive value, which indicates that the total porosity in the coating is contributed by both 2D pores and 3D pores. However, at this point, the normalized ST is close to zero. Compared with porosity, 2D pore density and normalized ST show a better fit, and the two are approximately proportional to each other. In contrast, porosity

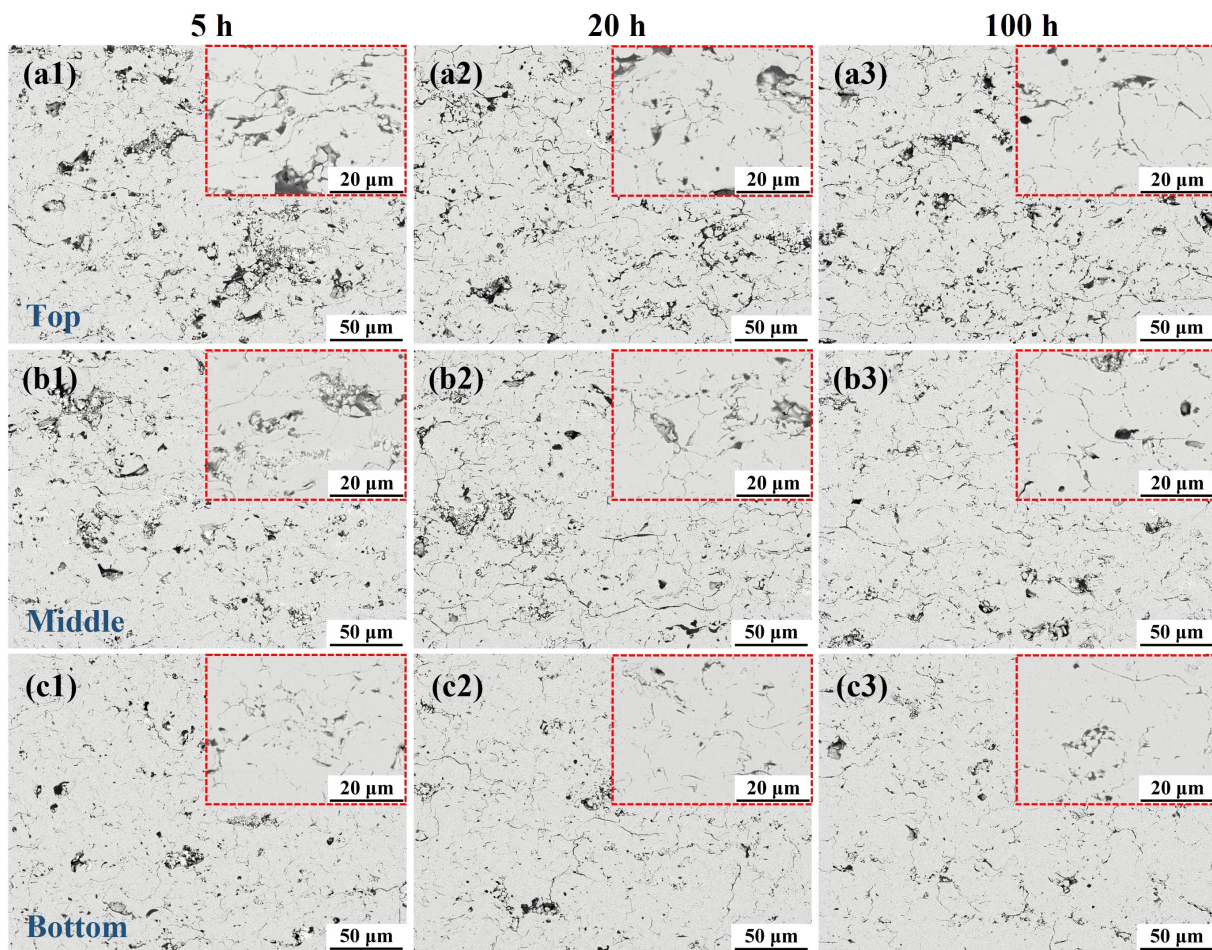


Fig. 13 Evolution of cross-sectional morphology after 1300 °C heat exposure: (a) top region, (b) middle region, and (c) bottom region.

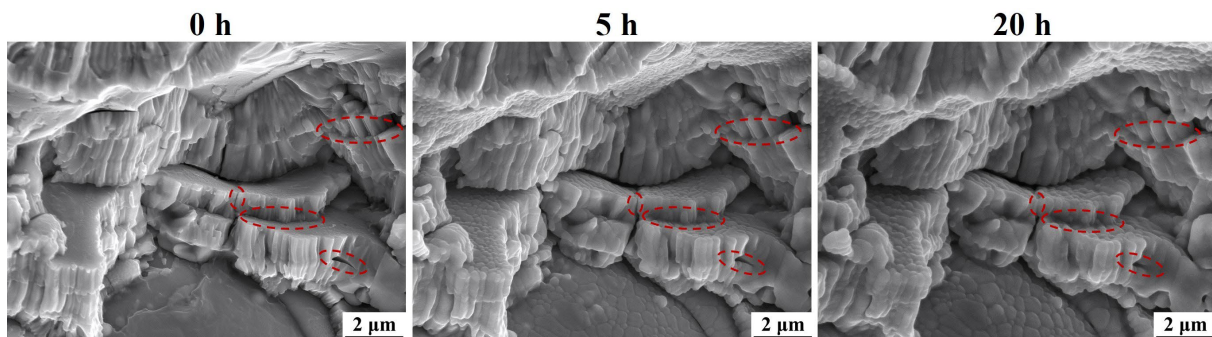


Fig. 14 *In situ* changes in 2D pores before and after thermal exposure at 1300 °C.

cannot well reflect the ST of the coating, and using it to predict the coating's ST will result in large errors. In addition, by comparing different regions, it can be observed that the fitting curve of the bottom region has a smaller y -intercept, which is related to the fewer pores in the dense bottom.

Therefore, the 2D pore network formed by the interconnection of pores between unbonded splats and microcracks within splats is the reason that plasma-sprayed TBCs have high ST. Meanwhile, the healing of 2D pores during the sintering process is the main reason for the increase in coating hardness and elastic modulus, as well as the decrease in ST. During high-temperature service, the coating undergoes sintering, which leads to an increase in elastic modulus. This causes an increase in internal stress and a decrease in ST. Eventually, excessive SERR triggers crack propagation, resulting in coating spallation and failure.

5.2.3 Failure mechanism dominated by sintering and oxidation

In reality, during the service of TBCs, sintering and oxidation occur simultaneously. Due to exposure to high temperatures, the ceramic TC undergoes sintering stiffening, which in turn increases the stress and SERR. At the same time, due to oxidation at high temperatures, the TGO continuously thickens, which also significantly increases the stress in the coating. Therefore, to investigate the changes in stress and SERR under the combined effect of sintering and oxidation, this study simulated the thermal cycling process of TBCs, during which both TC stiffening and TGO thickening occur simultaneously. As shown in Figs. 17(a) and 17(b), during the thermal cycling process, both the maximum normal stress and the maximum shear stress occur in the vicinity of the TGO. As the TGO oxidizes and the elastic modulus of the

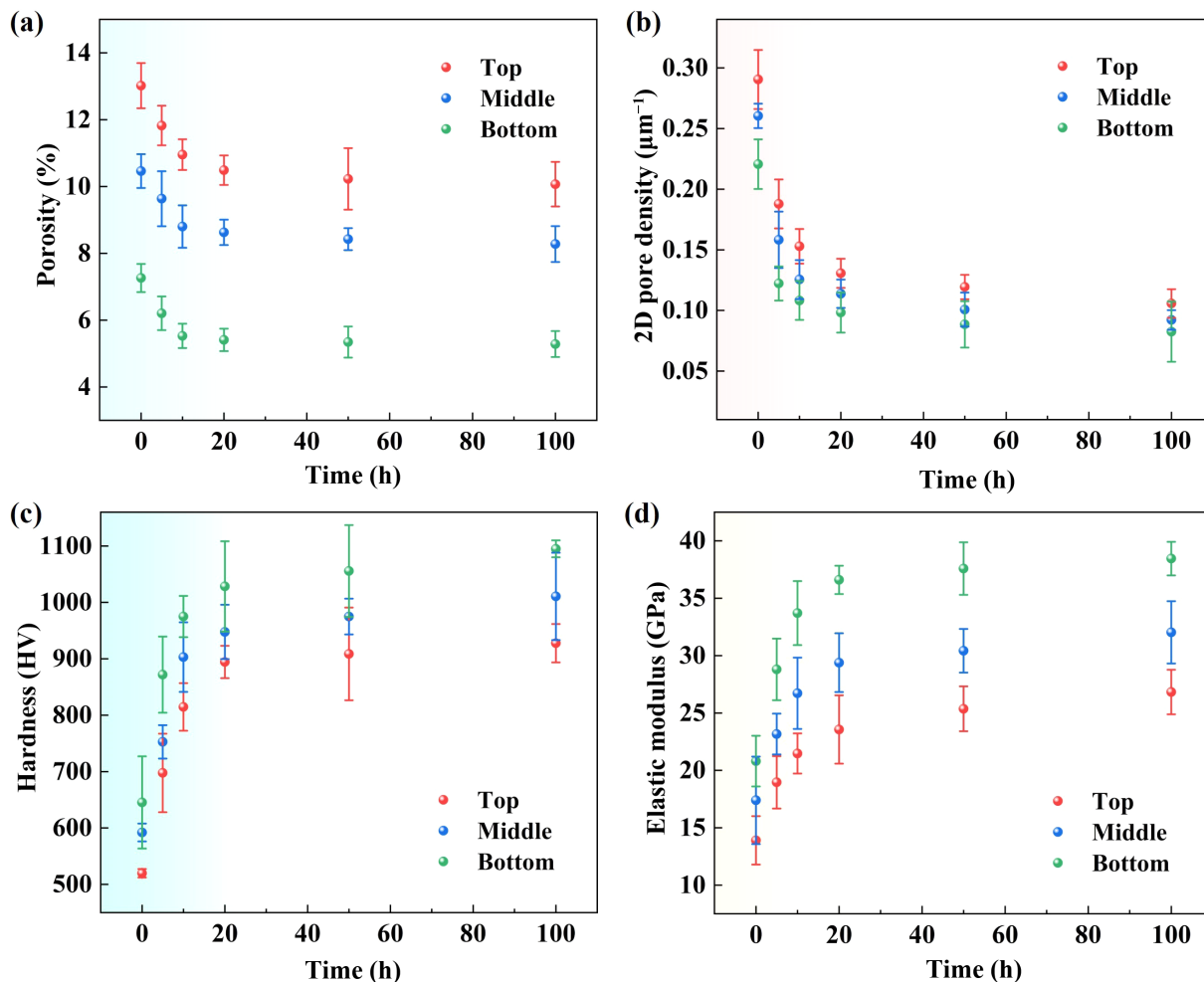


Fig. 15 Variation of pore structure parameters and mechanical properties of gradient TBC with thermal exposure time at 1300 °C: (a) porosity, (b) 2D pore density, (c) hardness, and (d) elastic modulus.

ceramic TC increases, the stress at the tip of the horizontal crack gradually increases. Figure 17(c) shows that within the initial 5 cycles, the SERR increases sharply, while in the subsequent cycles, it grows steadily. It can be anticipated that due to the synergistic effect of sintering and oxidation, the SERR will continue to increase, ultimately leading to coating failure. In addition, after the same number of thermal cycles, the SERR of the gradient-structured coating is always lower than that of the conventional lamellar porous coating. This implies that the gradient structure can not only improve the cracking resistance of the coating but also reduce the cracking driving force. A smaller SERR indicates that the coating is less prone to cracking, which is consistent with the actual thermal cycling results, in which the gradient coating has a longer lifespan than the porous lamellar structure.

5.3 Mechanism of high insulation and long lifespan

Figure 18 shows the influence of the vertical crack spacing on the coating stress and horizontal crack propagation driving force. Figures 18(a) and 18(b) show that as the vertical crack spacing increases, both the normal stress and shear stress increase significantly at first and then stabilize. For the 2-mm-thick gradient TBCs, when the vertical crack spacing is less than 8 mm, the crack spacing has a significant impact on the stress, whereas when the spacing exceeds 8 mm, its influence on the stress becomes minor. Figure 18(c) demonstrates the relationship between the SERR at the horizontal crack tip within a thick gradient coating and the vertical crack spacing. When the vertical

crack spacing is 1 mm, the SERR at the horizontal crack tip of the cracking-prone interface is 17.4 N·m⁻¹. At a spacing of 8 mm, the SERR at the crack tip is 96.5 N·m⁻¹, which is 5.5 times that at a spacing of 1 mm. When the spacing is 20 mm, the SERR at the crack tip reaches 106.7 N·m⁻¹, 6.1 times the value at a spacing of 1 mm. The variation trend of SERR with vertical crack spacing in the gradient thick coating is similar to that of stress. When the crack spacing is greater than 8 mm, the influence of crack spacing on SERR is minor; when the crack spacing is less than 8 mm, SERR decreases significantly as the crack spacing decreases. Therefore, gradient columnar TBCs need to have a smaller vertical crack spacing, thereby achieving a lower SERR and improving the lifespan of the coating.

In general, whether a TBC cracks depends on the competition between the SERR (also referred to as G) and the resistance to crack propagation (which is positively correlated with fracture toughness). A horizontal crack will propagate only when G exceeds the critical value. For TBCs without vertical cracks, G can be expressed as Eq. (4) [28,59]:

$$G = \frac{hE(\Delta\alpha \cdot \Delta T)^2}{2(1-\nu)} \quad (4)$$

where h is the distance from the horizontal crack tip to the coating surface; E is the elastic modulus of the coating; $\Delta\alpha$ is the difference in thermal expansion coefficients between the coating and the substrate; ΔT is the temperature difference between the operating

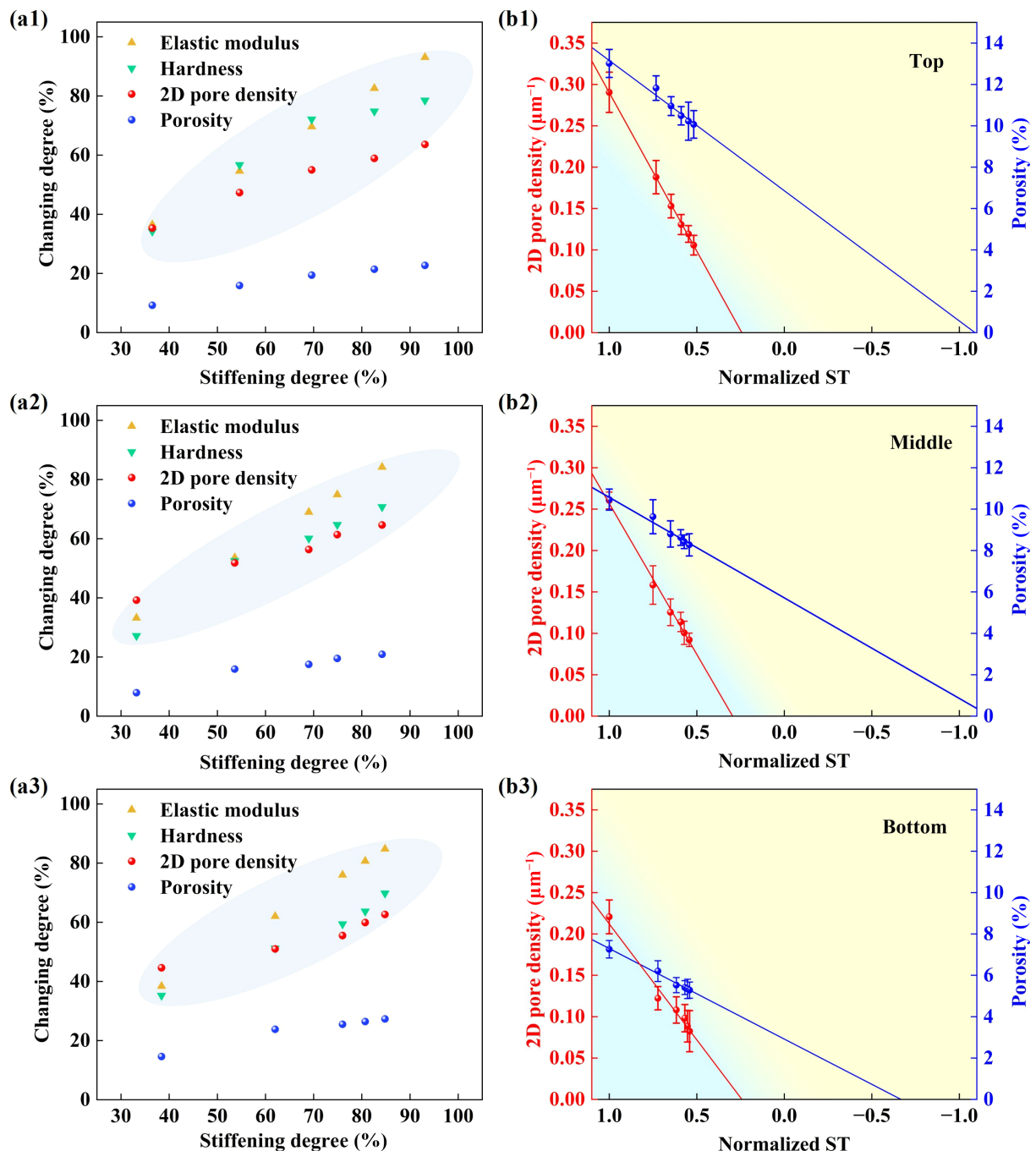


Fig. 16 Correlation between performance evolution and structural changes: (a) degree of change of different properties and (b) variations of 2D pore density and porosity with normalized ST.

temperature and room temperature; ν is Poisson's ratio of the coating.

After thermal exposure, the coating undergoes sintering and stiffening, and the G value increases significantly, eventually exceeding the critical value G_{IC} , leading to cracking and spalling. The critical crack propagation driving force (G_{IC}) can be expressed by Eq. (5) [60]:

$$G_{IC} = \frac{K_{IC}^2}{E} (1 - \nu^2) \quad (5)$$

where K_{IC} is the fracture toughness of the coating.

For the gradient TBCs in this study, compared with the conventional porous lamellar TBCs, their dense toughening layer

at the bottom has a higher K_{IC} , enabling it to withstand a larger G without fracturing. Thus, the advantages of the gradient columnar structure can be observed. On one hand, due to the toughened bottom layer, the gradient-structured TBCs exhibit a high critical G_{IC} . On the other hand, when vertical cracks are present, G within the coating is further reduced, and a smaller crack spacing corresponds to a smaller G .

In many previous studies, columnar structures were fabricated to enhance the lifespan of TBCs. The normalized lifespans of different columnar coatings relative to traditional coatings are shown in Fig. 19(a) [20,28,29,61–68]. TBCs with a very small intercolumnar pore spacing (L , including vertical crack spacing) can be prepared by EB-PVD and PS-PVD. Compared with

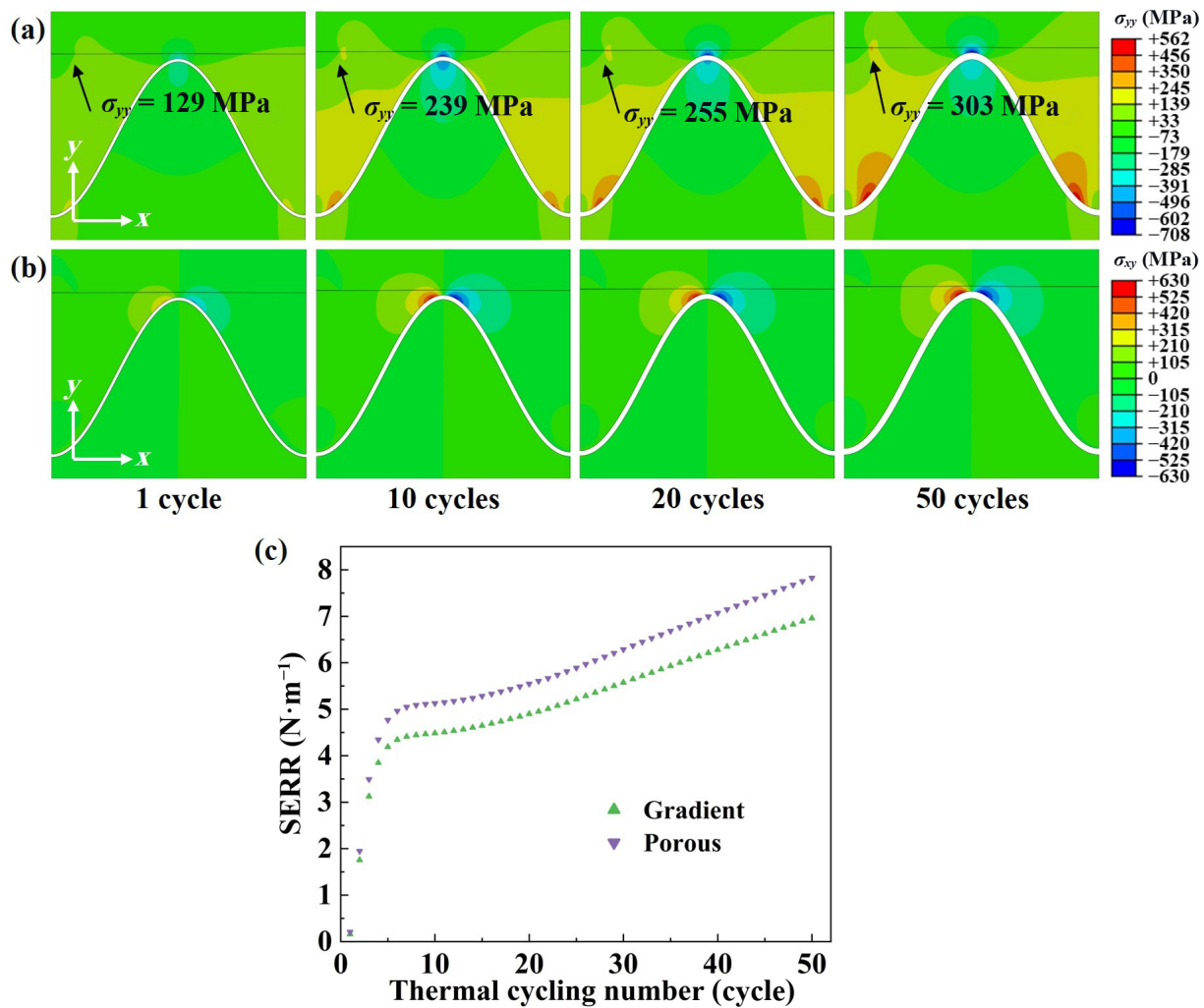


Fig. 17 Effect of thermal cycles on stress and SERR: (a) normal stress, (b) shear stress, and (c) variation of SERR with number of thermal cycles.

conventional APS lamellar TBCs, their lifespan is significantly improved. In addition, the lifespan of DVCs, which are obtained by introducing vertical cracks into dense coatings, is also improved. From these studies, it appears that when the influence of coating thickness is not considered, a smaller L tends to correspond to a longer lifespan. However, the actual situation is more complex because lifespan is also related to the coating's microstructure and mechanical properties. Recently, vertical cracks were fabricated in porous lamellar TBCs via solution precursor plasma spraying or by subjecting the coatings to thermal shock after plasma spraying, resulting in columnar/lamellar bimodal-structured TBCs (which also belong to PVC). Due to their porosity, these bimodal-structured TBCs exhibit a low elastic modulus, which leads to a reduced driving force for crack propagation, thereby improving the lifespan. However, due to the size limitation of individual splats in plasma spraying, it is difficult to achieve an L as small as that in EB-PVD; on the other hand, because of the lamellar porous bottom, columnar/lamellar bimodal-structured TBCs are still prone to cracking and spallation. In this work, the crack resistance of the coating can be further improved through the pore gradient structure along the coating thickness direction, thereby further extending its lifespan.

A long lifespan and high thermal insulation are two fundamental performance requirements for next-generation TBCs. However, in traditional research on TBCs, due to the

limitations of the monostructure, it is difficult for coatings to achieve both properties simultaneously, as shown in Fig. 19(b) [18,28,37,50,64,66,69–72] and Fig. 19(c) (including DVC [18], PS-PVD [50], EB-PVD [70], double-layer [72], and PVC [28]). TBCs prepared by EB-PVD and PS-PVD have a long lifespan, but their UTR is low. The optimization of thermal insulation capability and lifespan through the structure of APS-prepared double-layer coatings is also very limited. Compared with the traditional APS lamellar structure, the DVC coating structure has an improved lifespan but at the expense of thermal insulation capability. Columnar/lamellar bimodal-structured TBCs have a long lifespan while maintaining their thermal insulation capability, yet the improvement in lifespan remains limited. In this study, compared with traditional APS lamellar TBCs, thick gradient columnar TBCs exhibit a significantly improved lifespan while maintaining a high thermal insulation capability.

In summary, the synergistic effect of the macro-columnar, mesogradient, and microlamellar structures constitutes the mechanism behind the high thermal insulation and long lifespan of the trimodal-structured TBCs. The microlamellar structure endows the coatings with both high thermal insulation capability and high ST, yet these properties degrade after thermal exposure. For the mesogradient structure, its porous top region not only enhances the thermal insulation but also reduces the SERR of the TBCs due to its low elastic modulus, while its dense bottom region improves the crack resistance of TBCs. At the macroscale, the

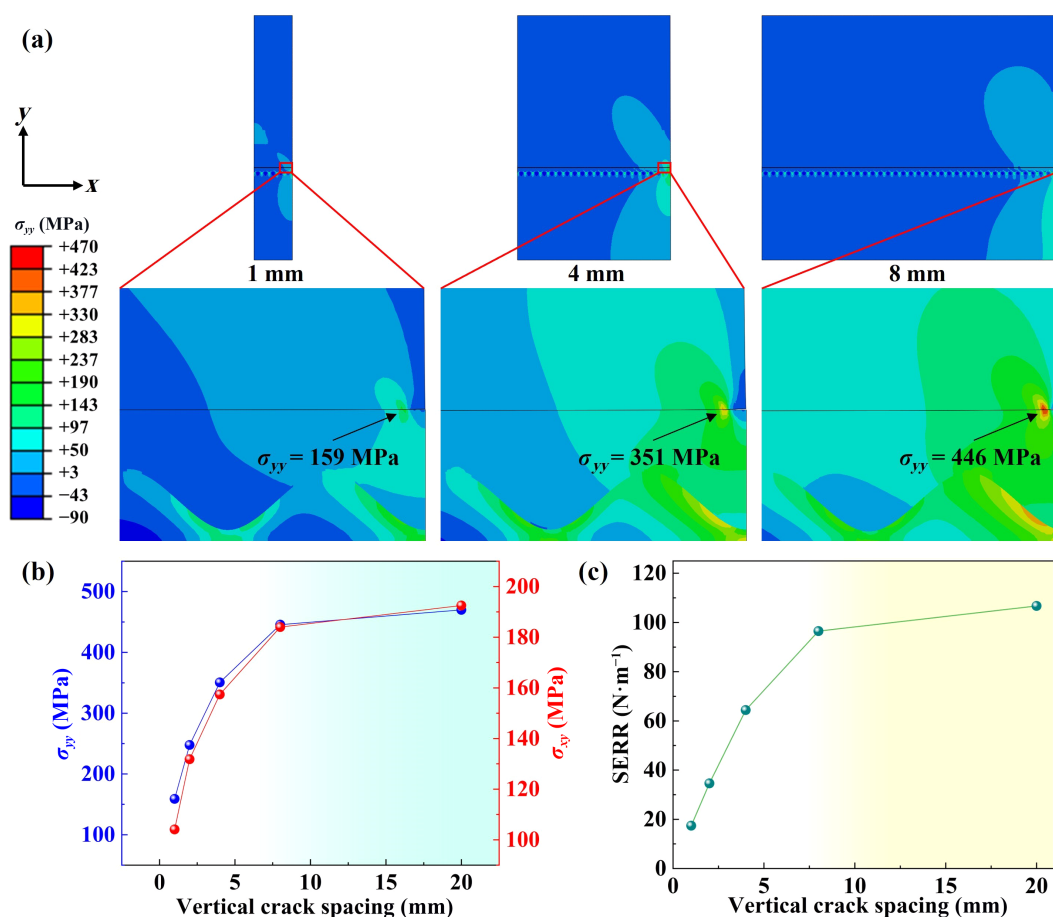


Fig. 18 Effect of vertical crack spacing on stress and SERR: (a, b) stress and (c) SERR.

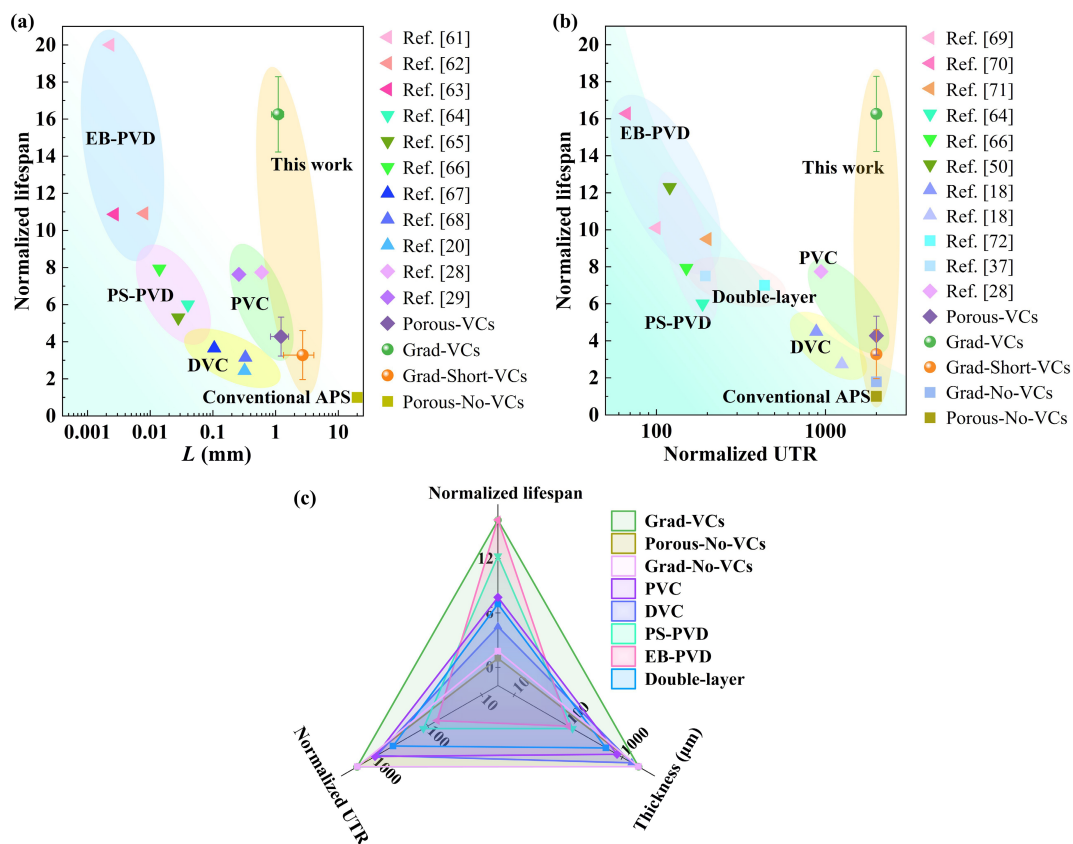


Fig. 19 (a) Relationship between normalized lifespan and L , (b) relationship between normalized lifespan and thermal insulation, and (c) performance comparison of different TBCs.

columnar structure divided by vertical cracks effectively relieves the internal stress of the TBCs, compensates for the reduced ST of the coatings caused by sintering, and lowers the driving force for crack propagation inside the coatings. In addition, vertical cracks can alter the propagation direction of horizontal cracks and hinder their continuous extension. These structural characteristics work together to explain why the trimodal-structured TBCs can exhibit high thermal insulation and a long lifespan.

6 Conclusions

In this work, a trimodal-structured TBC with macro-columnar, mesogradient, and microlamellar structures was designed and fabricated. This TBC exhibits a significantly extended lifespan while maintaining high thermal insulation performance. The mechanism underlying the high thermal insulation and long-lifespan service of the trimodal-structured TBC was analyzed and discussed. The conclusions of this study are as follows:

1) Under the premise of equivalent thermal insulation, a trimodal-structured thick TBC with macro-columnar, mesogradient, and microlamellar structures was fabricated. Its lifespan is approximately 16 times that of conventional lamellar TBCs, nearly 4 times that of one-way designed columnar TBCs, and 9 times that of one-way designed gradient TBCs.

2) The combined effect of lowering the driving force and increasing the cracking resistance significantly retards crack propagation. The eventual failure is attributed to the synergistic effect of sintering-induced stiffening of the ceramic TC and oxidation-induced thickening of the TGO.

3) The inside-out method of forming vertical cracks can generate vertical cracks with a better structure within the gradient coating. The resulting smaller crack spacing and greater crack depth are key factors contributing to the superior lifespan of the trimodal-structured TBC.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Nos. 52371075 and 51801148), the National Training Program of Innovation and Entrepreneurship for Undergraduates (No. S202510698546), the Young Elite Scientists Sponsorship Program by CAST (No. YESS20200083), the Young Talent fund of University Association for Science and Technology in Shaanxi, China (No. 20190403), and the Fundamental Research Funds for the Central Universities (No. xzy012022057).

Author contributions

Shuo-Cong Yang: data curation, formal analysis, investigation, methodology, software, and writing – original draft. Hai-Lin Yang: data curation, formal analysis, investigation, methodology, software, and writing – original draft. Run-Ze Yu: data curation, formal analysis, investigation, and methodology. Xue-Ting Jia: data curation, formal analysis, and investigation. Itfaq Ali: data curation, formal analysis, and investigation. Hussain Sajjad: formal analysis, investigation, and software. Guang-Rong Li: conceptualization, funding acquisition, methodology, resources, supervision, and writing – review and editing. Zhi-Yuan Wei: formal analysis, investigation, and validation. Guan-Jun Yang: conceptualization, supervision, and writing – review and editing. Yasir Muhammad: investigation, resources, and validation, supervision, and writing – review and editing.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article. The author Guan-Jun Yang is the Editorial Committee member of this journal.

References

- [1] Padture NP, Gell M, Jordan EH. Thermal barrier coatings for gas-turbine engine applications. *Science* 2002, **296**: 280–284.
- [2] Zhang ZJ, Sun J, Liu GH, et al. High toughness and CMAS resistance of $\text{REAlO}_3/\text{RE}_2\text{Zr}_2\text{O}_7$ (RE = La, Nd, Sm, Eu, Gd, and Dy) composites with eutectic composition for thermal barrier coatings. *J Adv Ceram* 2024, **13**: 800–809.
- [3] Padture NP. Advanced structural ceramics in aerospace propulsion. *Nat Mater* 2016, **15**: 804–809.
- [4] Gan MD, Lai LP, Wang JK, et al. Suppressing the oxygen-ionic conductivity and promoting the phase stability of the high-entropy rare earth niobates via Ta substitution. *J Mater Sci Technol* 2025, **209**: 79–94.
- [5] Clarke DR, Oechsner M, Padture NP. Thermal-barrier coatings for more efficient gas-turbine engines. *MRS Bull* 2012, **37**: 891–898.
- [6] Gan MD, Lu TL, Yu W, et al. Capturing and visualizing the phase transition mediated thermal stress of thermal barrier coating materials via a cross-scale integrated computational approach. *J Adv Ceram* 2024, **13**: 413–428.
- [7] Guo YQ, Guo L, Liu KY, et al. Mechanical properties and simulated thermal conductivity of biomimetic structured PS-PVD ($\text{Gd}_{0.9}\text{Yb}_{0.1}$) $_2\text{Zr}_2\text{O}_7$ thermal barrier coatings. *J Mater Sci Technol* 2024, **182**: 33–40.
- [8] Yang ZS, Li Y, Pan W, et al. Abnormal thermal expansion coefficients in $(\text{Nd}_{1-x}\text{Dy}_x)_2\text{Zr}_2\text{O}_7$ pyrochlore: The effect of low-lying optical phonons. *J Adv Ceram* 2023, **12**: 1001–1014.
- [9] Chen L, Li BH, Feng J. Rare-earth tantalates for next-generation thermal barrier coatings. *Prog Mater Sci* 2024, **144**: 101265.
- [10] Li GR, Liu T, Luo XT, et al. Tailoring sintering-resistant thermal barrier coatings by considering critical healing width of two-dimensional interlamellar pores. *J Adv Ceram* 2023, **12**: 1317–1330.
- [11] Vaßen R, Jarligo MO, Steinke T, et al. Overview on advanced thermal barrier coatings. *Surf Coat Tech* 2010, **205**: 938–942.
- [12] Wang JK, Chen L, Li BH, et al. Evolutions of mechanical and thermal properties of $\text{TmNbO}_4/\text{Tm}_3\text{NbO}_7$ composites as protective coating materials. *J Adv Ceram* 2024, **13**: 1771–1785.
- [13] Wang XF, Xiang HM, Sun X, et al. Mechanical properties and damage tolerance of bulk $\text{Yb}_3\text{Al}_5\text{O}_{12}$ ceramic. *J Mater Sci Technol* 2015, **31**: 369–374.
- [14] Li CJ, Dong H, Ding H, et al. The correlation of the TBC lifetimes in burner cycling test with thermal gradient and furnace isothermal cycling test by TGO effects. *J Therm Spray Technol* 2017, **26**: 378–387.
- [15] Wei ZY, Meng GH, Chen L, et al. Progress in ceramic materials and structure design toward advanced thermal barrier coatings. *J Adv Ceram* 2022, **11**: 985–1068.
- [16] Lu Z, Kim MS, Myoung SW, et al. Thermal stability and mechanical properties of thick thermal barrier coatings with vertical type cracks. *T Nonferr Metal Soc* 2014, **24**: s29–s35.
- [17] Scriveri A, Rizzi G, Berndt CC. Enhanced thick thermal barrier coatings that exhibit varying porosity. *Mat Sci Eng A—Struct* 2008, **476**: 1–7.
- [18] Guo HB, Vaßen R, Stöver D. Thermophysical properties and thermal cycling behavior of plasma sprayed thick thermal barrier coatings. *Surf Coat Tech* 2005, **192**: 48–56.
- [19] Guo HB, Vaßen R, Stöver D. Atmospheric plasma sprayed thick thermal barrier coatings with high segmentation crack density. *Surf Coat Tech* 2004, **186**: 353–363.
- [20] Izadinia M, Soltani R, Sohi MH. Effect of segmented cracks on TGO growth and life of thick thermal barrier coating under isothermal oxidation conditions. *Ceram Int* 2020, **46**: 7475–7481.
- [21] Mehboob G, Xu T, Li GR, et al. Strain-induced cracking behavior of

- coating/substrate systems and strain tolerant design for thick coatings. *Coatings* 2020, **10**: 1066.
- [22] Shinde SV, Gildersleeve V EJ, Johnson CA, *et al.* Segmentation crack formation dynamics during air plasma spraying of zirconia. *Acta Mater* 2020, **183**: 196–206.
- [23] Jiang P, Sun F, Chen YW, *et al.* Oxide growth in high-strain tolerance thermal barrier coating with segmented vertical cracks. *Ceram Int* 2024, **50**: 25025–25033.
- [24] Li P, Jin XC, Lu P, *et al.* Comparative study on microstructure evolution and failure mechanisms of ordinary and refurbished EB-PVD TBC under cyclic oxidation. *J Adv Ceram* 2023, **12**: 1805–1820.
- [25] Hu DY, Lv ZZ, Liu HY, *et al.* Characterization and mechanical modeling of interfacial damage in EB-PVD thermal barrier coatings considering multiple failure factors. *J Mater Sci Technol* 2024, **190**: 42–55.
- [26] Karger M, Vaßen R, Stöver D. Atmospheric plasma sprayed thermal barrier coatings with high segmentation crack densities: Spraying process, microstructure and thermal cycling behavior. *Surf Coat Tech* 2011, **206**: 16–23.
- [27] Cheng B, Yang N, Zhang Q, *et al.* Sintering induced the failure behavior of dense vertically crack and lamellar structured TBCs with equivalent thermal insulation performance. *Ceram Int* 2017, **43**: 15459–15465.
- [28] Wei JX, Sajjad H, Zeng ZY, *et al.* A bimodal-structured coating with columnar/lamellar trans-scale features for strain-tolerant and thermal insulative performances. *J Mater Sci Technol* 2026, **247**: 29–43.
- [29] Kumar R, Cietek D, Jiang C, *et al.* Influence of microstructure on the durability of gadolinium zirconate thermal barrier coatings using APS & SPPS processes. *Surf Coat Tech* 2018, **337**: 117–125.
- [30] Rabiei A, Evans AG. Failure mechanisms associated with the thermally grown oxide in plasma-sprayed thermal barrier coatings. *Acta Mater* 2000, **48**: 3963–3976.
- [31] Ahmadian S, Jordan EH. Explanation of the effect of rapid cycling on oxidation, rumpling, microcracking and lifetime of air plasma sprayed thermal barrier coatings. *Surf Coat Tech* 2014, **244**: 109–116.
- [32] Wei ZY, Cai HN, Li CJ. Comprehensive dynamic failure mechanism of thermal barrier coatings based on a novel crack propagation and TGO growth coupling model. *Ceram Int* 2018, **44**: 22556–22566.
- [33] Su XR, Zhang CQ, Huang LY, *et al.* Region-function-matching design for YSZ-based thermal barrier coatings enables long thermal cyclic lifespan. *J Am Ceram Soc* 2024, **107**: 8716–8731.
- [34] Pyeon J, Kang KM, Kim BG, *et al.* Mechanisms of enhanced thermal durability in porosity-controlled multilayer thermal barrier coatings. *Materials* 2025, **18**: 917.
- [35] Liu LQ, Xu WH, Shi JM, *et al.* Plasma sprayed thermal barrier coatings with outstanding ultrahigh temperature thermal shock resistances through gradient porosity level optimizations. *Ceram Int* 2025, **51**: 17484–17491.
- [36] Cheng B, Wei ZY, Chen L, *et al.* Prolong the durability of $\text{La}_2\text{Zr}_2\text{O}_7/\text{YSZ}$ TBCs by decreasing the cracking driving force in ceramic coatings. *J Eur Ceram Soc* 2018, **38**: 5482–5488.
- [37] Xie ZL, Li C, Zhang HX, *et al.* Durable $\text{GdTaO}_4/\text{YSZ}$ double-ceramic-layer thermal barrier coatings against ultrahigh-temperature thermal shock. *Ceram Int* 2025, **51**: 29781–29791.
- [38] Liu GL, Zhu L, Li XY, *et al.* Achieving durable double-layered thermal barrier coatings by tailoring multi-scale structures. *J Adv Ceram* 2024, **13**: 2068–2086.
- [39] Wu YM, Hong D, Zhong X, *et al.* Design and evaluation of multilayer $\text{Yb}_2\text{Hf}_3\text{O}_{12}$ -based T/EBs with enhanced thermal stability for high-temperature applications. *J Adv Ceram* 2025, **14**: 9221139.
- [40] Esmaeilkhani AH, Sharifianjazi F, Ahmadi E, *et al.* Thermal barrier coating with improved durability: An overview of doped, nanostructured, multilayered, and gradient-structured zirconia-based thermal barrier coatings. *Mater Today Commun* 2023, **37**: 107514.
- [41] Shi TJ, Zhao T, Guo YQ, *et al.* Microstructural optimization of $\text{Gd}_2\text{O}_3\text{--Yb}_2\text{O}_3\text{--Y}_2\text{O}_3$ co-stabilized ZrO_2/YSZ coatings with enhanced thermal shock resistance. *Mater Design* 2025, **254**: 114142.
- [42] Pedrizzetti G, Scrinzi E, Giubolini E, *et al.* Influence of microstructural parameters on thermal cycling behavior of DVC-TBC systems. *Surf Coat Tech* 2025, **499**: 131881.
- [43] Li GR, Huang LY, Liu GL, *et al.* Stiffening-resistant composite TBCs counteracting the substrate constraint effect during thermal exposure. *J Alloy Compd* 2024, **972**: 172832.
- [44] Li CJ, Li Y, Yang GJ, *et al.* A novel plasma-sprayed durable thermal barrier coating with a well-bonded YSZ interlayer between porous YSZ and bond coat. *J Therm Spray Technol* 2012, **21**: 383–390.
- [45] Meng GH, Liu H, Liu MJ, *et al.* Highly oxidation resistant MCrAlY bond coats prepared by heat treatment under low oxygen content. *Surf Coat Tech* 2019, **368**: 192–201.
- [46] Li GR, Xie H, Yang GJ, *et al.* A comprehensive sintering mechanism for TBCs—Part I: An overall evolution with two-stage kinetics. *J Am Ceram Soc* 2017, **100**: 2176–2189.
- [47] Li GR, Tang CH, Yang GJ. Dynamic-stiffening-induced aggravated cracking behavior driven by metal-substrate-constraint in a coating/substrate system. *J Mater Sci Technol* 2021, **65**: 154–163.
- [48] Wei ZY, Cai HN, Feng RX, *et al.* Dynamic crack growth mechanism and lifetime assessment in plasma sprayed thermal barrier system upon temperature cycling. *Ceram Int* 2019, **45**: 14896–14907.
- [49] Cheng B, Yang GJ, Zhang Q, *et al.* Gradient thermal cyclic behaviour of $\text{La}_2\text{Zr}_2\text{O}_7/\text{YSZ}$ DCL-TBCs with equivalent thermal insulation performance. *J Eur Ceram Soc* 2018, **38**: 1888–1896.
- [50] Gao LH, Guo HB, Wei LL, *et al.* Microstructure, thermal conductivity and thermal cycling behavior of thermal barrier coatings prepared by plasma spray physical vapor deposition. *Surf Coat Tech* 2015, **276**: 424–430.
- [51] Renteria AF, Saruhan B, Schulz U, *et al.* Effect of morphology on thermal conductivity of EB-PVD PYSZ TBCs. *Surf Coat Tech* 2006, **201**: 2611–2620.
- [52] Guo HB, Kuroda S, Murakami H. Microstructures and properties of plasma-sprayed segmented thermal barrier coatings. *J Am Ceram Soc* 2006, **89**: 1432–1439.
- [53] Dong H, Yang GJ, Li CX, *et al.* Effect of TGO thickness on thermal cyclic lifetime and failure mode of plasma-sprayed TBCs. *J Am Ceram Soc* 2014, **97**: 1226–1232.
- [54] Shi JQ, Zhang TB, Sun B, *et al.* Isothermal oxidation and TGO growth behavior of NiCoCrAlY–YSZ thermal barrier coatings on a Ni-based superalloy. *J Alloy Compd* 2020, **844**: 156093.
- [55] Liu YZ, Zheng SJ, Zhu YL, *et al.* Microstructural evolution at interfaces of thermal barrier coatings during isothermal oxidation. *J Eur Ceram Soc* 2016, **36**: 1765–1774.
- [56] Evans AG, Mumm DR, Hutchinson JW, *et al.* Mechanisms controlling the durability of thermal barrier coatings. *Prog Mater Sci* 2001, **46**: 505–553.
- [57] Ni LY, Liu C, Huang H, *et al.* Thermal cycling behavior of thermal barrier coatings with HVOF NiCrAlY bond coat. *J Therm Spray Technol* 2011, **20**: 1133–1138.
- [58] Yang SS, Jiang YM, Chen MH, *et al.* Achieving superior interfacial stability of the typical MCrAlY bond coat by microstructural regulation. *J Mater Sci Technol* 2026, **266**: 115–126.
- [59] Shinozaki M, Clyne TW. A methodology, based on sintering-induced stiffening, for prediction of the spallation lifetime of plasma-sprayed coatings. *Acta Mater* 2013, **61**: 579–588.
- [60] Irwin GR. Fracture strength of relatively brittle structures and materials. *J Franklin I* 1970, **290**: 513–521.
- [61] Xiong K, Wang JR, Jin XC, *et al.* Failure behaviors of EB-PVD thermal barrier coatings under isothermal oxidation and thermal cycling conditions. *Surf Coat Tech* 2024, **478**: 130439.
- [62] Xu ZH, Wang ZK, Huang GH, *et al.* Thermal cycling behavior of EB-PVD TBCs on CVD platinum modified aluminide coatings. *J Alloy Compd* 2015, **637**: 226–233.
- [63] Sohn YH, Kim JH, Jordan EH, *et al.* Thermal cycling of EB-PVD/

- MCrAlY thermal barrier coatings: I. Microstructural development and spallation mechanisms. *Surf Coat Tech* 2001, **146–147**: 70–78.
- [64] Kumar N, Gupta M, Mack DE, *et al.* Columnar thermal barrier coatings produced by different thermal spray processes. *J Therm Spray Techn* 2021, **30**: 1437–1452.
- [65] Zhang XF, Deng ZQ, Li H, *et al.* Al₂O₃-modified PS-PVD 7YSZ thermal barrier coatings for advanced gas-turbine engines. *npj Mat Degrad* 2020, **4**: 31.
- [66] Thibblin A, Jonsson S, Olofsson U. Influence of microstructure on thermal cycling lifetime and thermal insulation properties of yttria-stabilized zirconia thermal barrier coatings for diesel engine applications. *Surf Coat Tech* 2018, **350**: 1–11.
- [67] Wang Y, Guo HB, Gong SK. Thermal shock resistance and mechanical properties of La₂Ce₂O₇ thermal barrier coatings with segmented structure. *Ceram Int* 2009, **35**: 2639–2644.
- [68] Guo HB, Murakami H, Kuroda S. Thermal cycling behavior of plasma sprayed segmented thermal barrier coatings. *Mater Trans* 2006, **47**: 306–309.
- [69] Shen ZY, He LM, Xu ZH, *et al.* Rare earth oxides stabilized La₂Zr₂O₇ TBCs: EB-PVD, thermal conductivity and thermal cycling life. *Surf Coat Tech* 2019, **357**: 427–432.
- [70] Shen ZY, Xie M, Liu GX, *et al.* The thermal property and failure behaviors of SmErZrO thermal barrier coatings by EB-PVD. *Materialia* 2022, **25**: 101543.
- [71] Guo L, Guo HB, Peng H, *et al.* Thermophysical properties of Yb₂O₃ doped Gd₂Zr₂O₇ and thermal cycling durability of (Gd_{0.9}Yb_{0.1})₂Zr₂O₇/YSZ thermal barrier coatings. *J Eur Ceram Soc* 2014, **34**: 1255–1263.
- [72] Mehboob G, Liu GL, Wang SJ, *et al.* Matching design of thickness ratio to extend the lifespan of double-layered thermal-barrier coatings. *Ceram Int* 2024, **50**: 1505–1518.