RESEARCH ARTICLE

Le WANG, Yuelan DI, Ying LIU, Haidou WANG, Haoxing YOU, Tao LIU Effect of TGO on the tensile failure behavior of thermal barrier coatings

© Higher Education Press and Springer-Verlag GmbH Germany, part of Springer Nature 2019

Abstract Thermally grown oxide (TGO) may be generated in thermal barrier coatings (TBCs) after hightemperature oxidation. TGO increases the internal stress of the coatings, leading to the spalling of the coatings. Scanning electron microscopy and energy-dispersive spectroscopy were used to investigate the growth characteristics, microstructure, and composition of TGO after high-temperature oxidation for 0, 10, 30, and 50 h, and the results were systematically compared. Acoustic emission (AE) signals and the strain on the coating surface under static load were measured with AE technology and digital image correlation. Results showed that TGO gradually grew and thickened with the increase in oxidation time. The thickened TGO had preferential multi-cracks at the interface of TGO and the bond layer and delayed the strain on the surface of the coating under tensile load. TGO growth resulted in the generation of pores at the interface between the TGO and bond layer. The pores produced by TGO under tensile load delayed the generation of surface cracks and thus prolonged the failure time of TBCs.

Keywords thermally grown oxides, thermal barrier coatings, acoustic emission technology, digital image correlation, pores

Received March 9, 2019; accepted April 28, 2019

Le WANG, Ying LIU (⊠), Tao LIU School of Mechatronics Engineering, Nanchang University, Nanchang 330031, China E-mail: lying@ncu.edu.cn

Le WANG, Yuelan DI (🖾), Haidou WANG National Key Laboratory for Remanufacturing, Academy of Army Armored Forces, Beijing 100072, China E-mail: dylxinjic031@163.com

Haoxing YOU State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China

1 Introduction

The performance of aviation aircraft has been continuously improved in recent years, and several components of aeroengines, such as turbine blades, are expected to withstand increased temperatures. Thermal barrier coatings (TBCs) are widely used in the protection of aero-engine turbine blades because of their good thermal insulation performance and low cost [1-3]. TBCs are usually composed of a top ceramic coat (TC, 8YSZ, 8% Y₂O₃-stabilized ZrO₂) layer for thermal insulation, a metal bonding coat (BC, MCrAlY, M is usually Ni or Co) layer for improving adhesion, and a metal substrate composition [4]. However, a layer of thermally grown oxide (TGO) is formed at the interface between the ceramic and bonding layers and causes the coatings to spall during the service process [5,6]. TGO is a layer of dense oxides formed by metal elements in the bonding layer reacting with the air passing through the ceramic layer. TGO is usually a mixture of various oxides due to the numerous metal elements in the bonding layer and the diversity of reaction sites and modes. Different studies have presented varying views on the composition and growth of TGO. However, these studies have found that oxides, such as α -Al₂O₃ and Cr₂O₃, exist in the composition of TGO. Liu et al. [7] discovered that Ni(Al, Cr)₂O₄, γ -Ni, and NiO oxides are present in TGO. Hu et al. [8] reported that Y₃Al₅O₁₂ (YAG) and other substances also exist in TGO.

Many studies have focused on the growth characteristics and compositional morphologies of TGO [9,10] and linked TGO to coating damage cracks [11–14], but only a few have investigated the effect of TGO on the mechanical properties of TBCs. The uniform stress-strain relationship in the substrate is commonly used to approximate the stress-strain relationship in the coatings during static tensile testing. The stress and strain of coatings differ considerably from the stress and strain of the substrate. Furthermore, the stress and strain of coatings are asymmetrical. Digital image correlation (DIC) is a technique for detecting uneven strain. It is a quick and intuitive approach to calculate the strain of coatings by recording the displacement of similar points on the surface of coatings. However, DIC technology can only analyze surface strain through the displacement of visible surface spots; it cannot obtain the internal strain variations of coatings.

Acoustic emission (AE) technology is a non-destructive testing technique that detects conditions within the material and systematically characterizes the structural change and crack damage resulting from TGO growth inside TBCs. Researchers [15–17] used AE technology to detect changes in different crack patterns within TBCs via three- and four-point bend tests and a CaO-MgO-Al₂O₃-SiO₂ corrosion test. Yao et al. [18] used the fast Fourier analysis method to obtain the spectral characteristics of cracks during tensile testing and discovered different crack forms represented by different AE signals. However, AE technology entails a complicated operation, is susceptible to environmental conditions, and cannot intuitively obtain the relationship between crack damage and AE signals. The combination of AE and DIC can accurately identify the state of cracks and their formation patterns. Many studies [7,19,20] have discovered that TGO exhibits parabolic growth, which means the growth rate of TGO gradually decreases with the increase in oxidation time. TGO grows rapidly in the early stage of high-temperature oxidation, but the growth rate slows down after 50 h of oxidation [5,21]. This study focuses on the evolution of TGO under high-temperature oxidation for 50 h.

In this study, the growth characteristics of TGO in TBCs were systematically analyzed through scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and other characterization methods. The effect of TGO on the mechanical properties of coatings was investigated, and the damage characteristics of the coatings under tensile load were observed. First, samples were prepared within 50 h of high-temperature oxidation. A cross-section observation was performed via SEM and EDS to determine the growth behavior of TGO. Second, static tensile tests were conducted on the prepared specimens by using a universal testing machine. Third, the variations of TBCs under static load were measured with a charge-coupled device (CCD) camera and an AE detection device. Finally, DIC and AE data were analyzed to investigate the impact on the mechanical properties and damage characteristics of TGO under tensile load.

2 Experiment

Cylindrical specimens ($\Phi 25 \text{ mm} \times 5 \text{ mm}$) and static tensile specimens with an effective length of 50 mm were prepared from GH3128 nickel-based superalloy. After cleaning and sandblasting, a 100 µm NiCrAlY (Ni-22Cr-10Al-1Y, wt.%) bonding layer was fabricated on the substrate by atmospheric plasma spraying (APS). Then, a 350 µm 8YSZ (8 wt.% Y₂O₃-stabilized ZrO₂) ceramic layer was sprayed using APS technology. Table 1 presents the spraying parameters of NiCrAlY and 8YSZ.

The two samples were subjected to isothermal oxidation simultaneously. The samples were then placed in a muffle furnace with air circulation at room temperature (23 $^{\circ}C\pm$ 1 °C) and heated to 1050 °C at a rate of 8 °C/min. They were naturally cooled down to room temperature after each holding time. Three holding times of 10, 30, and 50 h were set for the oxidation. Cylindrical TBC samples after and before oxidation were cut along the cross section into small pieces measuring $10 \text{ mm} \times 10 \text{ mm} \times 5 \text{ mm}$. The samples were then ultrasonically cleaned and embedded in cylindrical epoxy resin. The observed section was ensured to be parallel to the cylindrical surface of one side of the epoxy resin. Subsequently, the observed surface was sand blasted, polished, and ultrasonically cleaned with alcohol. The morphologies and compositions of the interface between the ceramic and bonding layers before and after oxidation were analyzed through SEM equipped with EDS (SEM, ZEISS EVO18, Germany), and the growth rate of TGO was obtained.

Tensile tests were conducted on the tensile specimens by using a universal testing machine (AG-X, Shimadzu Corporation, Japan). The surface of the coating was artificially painted, and the sample was clamped. The AE probe was connected to the substrate with a coupling agent and tape, and the other end of the probe was connected to an AE microcomputer (Advantech IPC-610MB-L, China) with a display monitor. The specimens were subjected to a static tensile load at a constant rate of 0.3 mm/min. The AE microcomputer was turned on, and the AE signals were recorded. The movement of the black paint during the stretching of the coating was photographed and recorded simultaneously by a CCD camera. The light source was used to improve the clarity of the photos, which were saved at a rate of 1 photo per second until the coating began to peel off. Afterward, the photos were imported into the DIC analysis software to obtain the strain of the coatings under tensile load.

Table 1 Spraying parameters of NiCrAlY and 8YSZ

Specimen	Plasma gas $/(L \cdot min^{-1})$	Plasma gas pressure/MPa	Linear velocity $/(m \cdot min^{-1})$	Current /A	Voltage /V	Spray distance /mm	Single spraying thickness/mm	Carrier gas $/(L \cdot min^{-1})$	Powder feed rate/ $(g \cdot min^{-1})$
NiCrAlY	Ar 200, H ₂ 12.9	Ar 0.7, H ₂ 0.5	45	400	150	100	0.02	10	40
8YSZ	Ar 40, H ₂ 3	Ar 0.7, H ₂ 0.5	45	450	140	100	0.01	10	40

3 Results and discussions

3.1 Growth characteristics of TGO

After high-temperature oxidation, TGO began to form at the interface between the ceramic and bonding layers. Figure 1 shows a schematic view of the thickness measurement region of TGO. The thickness of TGO was measured using the method of average thickness, namely,

$$d = A/W, \tag{1}$$

where d is the thickness of TGO, A is the cross-section area of TGO, and W is the width of the image.



Fig. 1 TGO thickness measurement area

The continuous TGO region was divided into five parts on the average, and the same multiple SEM pictures were obtained from each part. According to Eq. (1), the measured TGO thicknesses was the average value of the five results obtained by the measured TGO areas on the image divided by the width of the image.

Figure 2 shows the line chart of the thickness variation of TGO. Overall, the growth rate of TGO gradually decreased as the oxidation time increased because TGO is a dense oxide film that reduces the contact between oxygen and metal elements; the rate of oxidation gradually slows down with the consumption of metal elements [22–24].

Figures 3(a)-3(h) show the SEM images and energy spectra of the cross sections of TBCs at different oxidation times. Figure 3(a) shows that the oxygen content in the coatings was negligible after spraying, indicating that almost no TGO was generated before high-temperature oxidation. After high-temperature oxidation, a thin, irregular oxide layer appeared at the interface of the ceramic and bonding layers, as shown in Figs. 3(c), 3(e), and 3(g). As the oxidation time increased, the TGO layer gradually thickened in an irregular pattern.

According to the cross-sectional energy spectra of the TBCs at different oxidation times (Fig. 3), the contents of



Fig. 2 Thickness variation of TGO

Ni, Cr, and Al in the metal elements of the bonding layer were high, and the content of Ni was the highest. After high-temperature oxidation, the contents of Cr, O, and Al became substantial, and the content of Ni was almost 0 in the TGO layer. However, Ni did not participate in oxidation before the high-temperature oxidation for 50 h. Only Al and Cr reacted with O. The reaction equations are as follows:

$$2[Al] + 3[O] \rightarrow Al_2O_3,$$
$$2[Cr] + 3[O] \rightarrow Cr_2O_3.$$

Figures 3(d), 3(f), and 3(h) show that the ratio of Cr to Al was almost the same under increasing oxidation time along the thickness direction of TGO. The same was observed for the ratio of Cr to Al in the initial bonding layer in Fig. 3(b), indicating that Cr and Al simultaneously reacted with O. Although Al and Cr can be oxidized, the Gibbs free energy of Al₂O₃ is larger than that of Cr₂O₃ [7]. Liang et al. [25] showed that the lattice mismatch between Al₂O₃ and the bonding layer is more severe than that between Cr₂O₃ and the bonding layer, and this difference leads to the fact that Cr₂O₃ is likely to grow along the original lattice of the bonding layer. Moreover, the content of Cr in the bonding layer is higher than that of Al. Thus, the content of Cr₂O₃ in TGO is the highest.

Figures 3(c), 3(e), and 3(g) show microscopic pores at the interface of TGO and the bond layer. As the hightemperature oxidation time increased, pore sizes gradually increased, and some even merged to form large pores.

Figures 3(b), 3(d), 3(f), and 3(h) show that the Ni content is large in the bonding layer, and almost no presence of Ni was found in TGO. Suo et al. [26] found that alloying elements of the oxidation interface undergo nonreciprocal diffusion and the Kirkendall effect during the oxidation of the bonding layer. At the interface of TGO and the bonding layer, Al and Cr in the bonding layer



Fig. 3 SEM images and line sweep energy spectra of TGO at different oxidation times: (a, b) before oxidation, (c, d) at 10 h, (e, f) at 30 h, and (g, h) at 50 h

diffused toward the ceramic layer. Conversely, Ni diffused toward the bonding layer, and the diffusion rates in the two directions differed. Al and Cr participated simultaneously in oxidation, whereas Ni was not a part of oxidation during the formation of TGO. Oxidation and diffusion led to the generation of tensile stress and horizontal creep, which formed many pores at the interface of TGO and the bonding layer. Studies have shown that pore shape is related to the creep mode [27]. Suppressed creep in the vertical direction of the interface leads to pancake-shaped pores, and anisotropic creep leads to hemispherical pores.

3.2 Effect of TGO on the mechanical properties of coatings

The movements of the coating surface under uniform tensile load were recorded by a CCD camera to derive spot movements on the surface of the coatings. The changes in the surface strain of the coatings until cracking obtained via DIC are shown in Fig. 4. Figure 4(a) shows the strain change curves of the initial cracking location on the coating surface under different oxidation times. The strain image changes shown in Fig. 4(b) are divided into four stages until the initiation of surface cracks:

1) The strain changed irregularly when the coatings were initially subjected to tensile load.

2) When the load increased with stretching, the surface strain of the coatings was in a periodic state, which is close to a sinusoidal curve. The maximum and minimum strains were like peaks and valleys that constantly moved in the same direction, respectively.

3) When the tensile load reached a certain stage, the strain in a small part of the coatings increased sharply.

4) Given that the strain sharply increased, a small part of the coatings reached their ultimate tensile strength, leading to cracks.

Figure 4(b) shows the strain curves of the first surface

crack point of the coatings under different oxidation times with the tensile time. The curves follow the four stages. With the strain curve of 50 h oxidation as an example, OAwas the first stage, and the surface strain of the coatings was small at this stage. As the strain increased, the coatings entered the strain fluctuation stage (the AB section). In this stage, the strain showed a fluctuating rising state. After the *B* inflection point, the strain at the cracking point of the coating surface increased sharply until cracks occurred. When the stress on the surface of the coatings exceeded the tensile limit, that is, the strain also increased to a certain value (Point *C*), the surface crack of the coatings initiated and expanded.

3.3 Effect of TGO on the damage characteristics of TBCs

The stress-strain relationship of the substrate during the stretching process and the AE events of the coatings with stretching time are shown in Fig. 5. The AE events during stretching were divided into four stages: A, B, C, and D. A is the elastic deformation stage; B is the surface vertical crack stage; C is the surface crack saturation transition stage; and D is the interface crack stage. Comparison of Fig. 5(a) with Figs. 5(b)-5(d) indicates that before and after the high-temperature oxidation, the TBCs presented a significant difference in AE signal in Stage A. The AE events before the high-temperature oxidation were almost zero in Stage A. However, after the high-temperature oxidation, gradually decaying AE signals were generated as soon as the coatings began to stretch in Stage A. With the increase in oxidation time, the AE events gradually increased in Stage A. The time when surface cracks began to appear was gradually delayed, but the AE events of the interface crack gradually decreased.

TGO was not formed before the high-temperature oxidation. When the tensile load was gradually increased,



Fig. 4 Variation in the surface strain of TBCs under uniform tensile load. (a) Cloud surface strain change with time; (b) strain curves of the coating surface with time



Fig. 5 Corresponding relationship between stress and strain of the substrate and AE signals as they change with time under tensile load. (a) 0 h; (b) 10 h; (c) 30 h; (d) 50 h

the stress applied to the coatings also gradually increased. Given that the stretching direction was parallel to the coating surface, surface cracks occurred preferentially after the stress exceeded the tensile resistance of the coatings. Section 3.1 indicates that after high-temperature oxidation, the presence of TGO causes an increasing number of pores at the interface between TGO and the bonding layer. When subjected to tensile load, these pores crack preferentially at the interface between TGO and the bonding layer, resulting in the generation of AE signals. As the tensile load continues to increase, crack propagation gradually decreases due to the large compressive stress at the interface between TGO and the bonding layer, resulting in a gradual attenuation of AE signals [28].

3.4 Effect of pores on the tensile failure of coatings

According to the results of SEM shown in Fig. 3, after the high-temperature oxidation of the TBCs, pores formed at the interface of TGO and the bonding layer, and the number of pores gradually increased as the TGO

thickened. These tiny pores exert a key influence on the mechanical behavior of the coatings during loading. Wei et al. [29] stated that pores can cause interface cracks. Micropores immediately expand to form microcracks under tensile load due to the low bearing capacity, which also causes AE signals to be generated at the beginning of stretching.

As the tensile strain increased, the microcracks gradually increased. These microvoids and microcracks contributed to the slow release of the TGO-bonding layer stress and provided a certain strain coordination effect. If no pore exists between the bonding layer and TGO, then the tight bond of the TGO-bonding layer interface can cause the bonding layer load to transfer immediately to TGO or even the ceramic layer. In this case, the strain of the ceramic layer will rapidly increase to the failure limit, which is presented by the surface cracks in Fig. 5(a) where the AE signals start at 1000 s. However, the appearance of micropores and microcracks causes the tensile load on the TGO to be lower than the tensile load on the bonding layer and the substrate, resulting in a delay in surface cracking time. The surface crack initiation time in Figs. 5(b)-5(d) is delayed from 1100 to 1500 s.

As the tensile strain increased, surface cracks also occurred in the coatings after the high-temperature oxidation. However, due to the multiple microcracks in the TGO layer, the AE signal density of the interface crack decreased when the surface cracks spread to the interface, as shown in Fig. 5. Therefore, the microcavity-microcrack structure contributed to the cooperation of the coatings to some extent and delayed the occurrence of failure.

Figure 6 is a schematic showing the effect of pores on the strain change of the TBCs before and after oxidation. Lines a–e in the coordinate axis correspond to the strain of images Figs. 6(a)–6(e) at a certain moment. Figure 6 also shows the ratio of strain to the time at which the uniform rate static tensile substrate is kept constant. Before oxidation, TGO was not contained in the coating, and the strain applied to the substrate was transmitted to the ceramic layer along a certain regularity and gradually increased with the increase in stretching time. When the surface strain of the ceramic layer reached ε_1 , surface cracks appeared at the ceramic layers, as shown in Figs. 6(a) and 6(b). This process also corresponds to the phenomenon of the AE signals' disappearance in the coatings before the appearance of surface cracks in Fig. 5(a). After oxidation, TGO formed at the interface between the ceramic and bonding layers. Many pores appeared at the interface between TGO and the bonding layer. During the static tensile process, the pores merged with one another to form large pores or microcracks. These microcracks and microvoids contributed to stress relaxation and provided strain coordination, which reduced the rate at which the interface of the bonding layer transferred strain to TGO. Therefore, the strain at the TGO and ceramic layer was lower than that at the ceramic layer before oxidation. As shown in Figs. 6(c) and 6(d), the strain at the ceramic layer and TGO was partially delayed compared with that before oxidation. Comparison of Figs. 6(b) and 6(d) shows that although they all occurred at time t_2 , the surface crack in Fig. 6(b) already initiated. However, the strain on the surface in Fig. 6(d) was still lower than ε_1 . Surface cracks did not appear due to the strain delay, indicating that the TBCs before high-temperature oxidation were prone to surface cracks. As stretching time continued to increase, the strain on the surface of the coatings after oxidation reached ε_1 until time t_3 . This result indicates that the pores at the interface between TGO and the bonding layer postponed the time of the appearance of



Fig. 6 Schematic of the influence of pores at the interface of TGO and the bonding layer on TBCs under tensile load

surface cracks after high-temperature oxidation, which is consistent with the finding that the surface crack initiation of the oxidized coatings in Fig. 4 takes longer time than that before oxidation. This finding is also consistent with the result that the occurrence time of the surface crack AE signals after oxidation is later than that before oxidation (Fig. 5).

4 Conclusions

In this study, SEM and EDS characterization methods were used to analyze the growth characteristics of TGO. AE and DIC techniques were applied to monitor simultaneously the microscopic deformation characteristics of TBCs under static tensile stress. The mechanical properties and damage characteristic of TGO on TBCs were summarized. The following conclusions were obtained.

1) After high-temperature oxidation, TGO was formed at the interface between the ceramic and bonding layers. TGO gradually grew and thickened as the oxidation time increased, but its growth rate gradually decreased.

2) The presence of TGO in TBCs affected the strain behavior of the coatings under mechanical loading, reduced strain fluctuations, and delayed the time of occurrence of surface cracks that caused interfacial cracks in the substrate during elastic deformation.

3) After TGO initiation, microscopic pores and cracks appeared at the interface between TGO and the bonding layer. When TGO thickened with increasing oxidation time, the number of pores also increased gradually. Under static load stretching, the pores could form interfacial cracks during the initial stage of tensile static load. The pores and interfacial cracks could reduce the transmission of tensile load and delay the generation of cracks.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant Nos. 51775553 and 51535011). Their assistance is acknowledged.

References

- Evans A G, Mumm D R, Hutchinson J W, et al. Mechanisms controlling the durability of thermal barrier coatings. Progress in Materials Science, 2001, 46(5): 505–553
- Zhang Q, Li C J, Li Y, et al. Thermal failure of nanostructured thermal barrier coatings with cold-sprayed nanostructured NiCrAIY bond coat. Journal of Thermal Spray Technology, 2008, 17(5–6): 838–845
- Padture N P, Gell M, Jordan E H. Thermal barrier coatings for gasturbine engine applications. Science, 2002, 296(5566): 280–284
- Toscano J, Naumenko D, Gil A, et al. Parameters affecting TGO growth rate and the lifetime of TBC systems with MCrAlYbondcoats. Materials and Corrosion, 2008, 59(6): 501–507
- 5. Torkashvand K, Poursaeidi E. Effect of temperature and ceramic

bonding on BC oxidation behavior in plasma-sprayed thermal barrier coatings. Surface and Coatings Technology, 2018, 349: 177–185

- Che C, Wu G Q, Qi H Y, et al. Uneven growth of thermally grown oxide and stress distribution in plasma-sprayed thermal barrier coatings. Surface and Coatings Technology, 2009, 203(20–21): 3088–3091
- Liu Y Z, Zheng S J, Zhu Y L, et al. Microstructural evolution at interfaces of thermal barrier coatings during isothermal oxidation. Journal of the European Ceramic Society, 2016, 36(7): 1765–1774
- Hu Y, Cai C Y, Wang Y G, et al. YSZ/NiCrAIY interface oxidation of APS thermal barrier coatings. Corrosion Science, 2018, 142: 22– 30
- Li Y, Li C J, Zhang Q, et al. Effect of chemical compositions and surface morphologies of MCrAIY coating on its isothermal oxidation behavior. Journal of Thermal Spray Technology, 2011, 20(1–2): 121–131
- Zhou S F, Xiong Z, Lei J B, et al. Influence of milling time on the microstructure evolution and oxidation behavior of NiCrAlY coatings by laser induction hybrid cladding. Corrosion Science, 2016, 103: 105–116
- Tailor S, Modi A, Modi S C. Effect of controlled segmentation on the thermal cycling behavior of plasma sprayed YSZ thick coatings. Ceramics International, 2018, 44(6): 6762–6768
- Evans H E. Oxidation failure of TBC systems: An assessment of mechanisms. Surface and Coatings Technology, 2011, 206(7): 1512–1521
- Yu Q M, Cen L, Wang Y. Numerical study of residual stress and crack nucleation in thermal barrier coating system with plane model. Ceramics International, 2018, 44(5): 5116–5123
- Shen Q, Yang L, Zhou Y C, et al. Effects of growth stress in finitedeformation thermally grown oxide on failure mechanism of thermal barrier coatings. Mechanics of Materials, 2017, 114: 228– 242
- Yang L, Yang T T, Zhou Y C, et al. Acoustic emission monitoring and damage mode discrimination of APS thermal barrier coatings under high temperature CMAS corrosion. Surface and Coatings Technology, 2016, 304: 272–282
- Yang L, Zhong Z C, You J, et al. Acoustic emission evaluation of fracture characteristics in thermal barrier coatings under bending. Surface and Coatings Technology, 2013, 232(10): 710–718
- Wang L, Ni J X, Shao F, et al. Failure behavior of plasma-sprayed yttria-stabilized zirconia thermal barrier coatings under three-point bending test via acoustic emission technique. Journal of Thermal Spray Technology, 2017, 26(1–2): 116–131
- Yao W B, Dai C Y, Mao W G, et al. Acoustic emission analysis on tensile failure of air plasma-sprayed thermal barrier coatings. Surface and Coatings Technology, 2012, 206(18): 3803–3807
- Shen Q, Yang L, Zhou Y C, et al. Models for predicting TGO growth to rough interface in TBCs. Surface and Coatings Technology, 2017, 325: 219–228
- Gürgen S, Diltemiz S F, Kushan M C. Oxidation and thermal shock behavior of thermal barrier coated 18/10CrNi alloy with coating modifications. Journal of Mechanical Science and Technology, 2017, 31(1): 149–155
- 21. Baskaran T, Arya S B. Role of thermally grown oxide and oxidation

resistance of samarium strontium aluminate based air plasma sprayed ceramic thermal barrier coatings. Surface and Coatings Technology, 2017, 326: 299–309

- Ma K K, Tang X C, Schoenung J M. Mechanistic investigation into the role of aluminum diffusion in the oxidation behavior of cryomilled NiCrAIY bond coat. Journal of Wuhan University of Technology-Materials Science Edition, 2016, 31(1): 35–43
- Liu X J, Wang T, Li C C, et al. Microstructural evolution and growth kinetics of thermally grown oxides in plasma sprayed thermal barrier coatings. Progress in Natural Science-Materials International, 2016, 26(1): 103–111
- Keyvani A, Bahamirian M. Oxidation resistance of Al₂O₃nanostructured/CSZ composite compared to conventional CSZ and YSZ thermal barrier coatings. Materials Research Express, 2016, 3(10): 105047

- Liang G Y, Zhu C, Wu X Y, et al. The formation model of Ni-Cr oxides on NiCoCrAlY-sprayed coating. Applied Surface Science, 2011, 257(15): 6468–6473
- Suo Z, Kubair D V, Evans A G, et al. Stresses induced in alloys by selective oxidation. Acta Materialia, 2003, 51(4): 959–974
- Pal S, Kubair D V. Finite element simulations of microvoid growth due to selective oxidation in binary alloys. Modelling and Simulation in Materials Science and Engineering, 2006, 14(7): 1211–1223
- Yu Q M, Cen L. Residual stress distribution along interfaces in thermal barrier coating system under thermal cycles. Ceramics International, 2017, 43(3): 3089–3100
- Wei S, Wang G, Yu J, et al. Competitive failure analysis on tensile fracture of laser-deposited material for martensitic stainless steel. Materials & Design, 2017, 118: 1–10