



Effects of the combined vacuum pre-oxidation on the microcracks initiation and propagation of thermal barrier coatings deposited by means of plasma spraying



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ABSTRACT

The chemical compositions and the residual stress of the thermally grown oxides (TGO) of thermal barrier coatings (TBCs) were characterized. Moreover, the relationship between the initiation and propagation of the microcracks in top coat and the evolution of TGO were systematically studied. The results indicate that the degradation mechanisms of TBCs prepared by atmospheric plasma spraying probably result from the weakened TGO area which is closely related to the change of the alumina phase transformation and the excessive presence of the spinel oxides as well as the propagation of the vertical surface cracks. Generally, the vertical surface cracks will propagate to the TGO area and subsequently meet with the horizontal cracks adjacent to the upper 50 μm area from the TGO. However, the propagation of the vertical surface cracks will be markedly suppressed when the strengthened TGO area occurs; while the initiation and propagation of the horizontal cracks above the TGO area can be significantly suppressed because the specific cracks aggregation can be found in the top coat. Furthermore, the textured (Al, Cr)₂O₃ formed at the bottom layer of TGO can strengthen the oxidation and corrosion resistance of TGO. The maximum magnitude of the steady state release rate G_{ss} can be delayed in the top coat, which can prolong the lifetime of TBCs.

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1. Introduction

Thermal barrier coatings system (TBCs) are widely used for the hot sections of gas turbines in the areas of aerospace and land-based engine in the past five decades, which can protect the parts from high temperature oxidation and corrosion [1,2]. In general, conventional TBCs systems usually consist of a 150–200 μm MCrAlY (M represents Ni, Co or Ni & Co) metallic bond coat deposited by means of plasma spraying process such as atmospheric plasma spraying (APS), low pressure plasma spraying (LPPS), vapor plasma spraying (VPS) and high velocity oxygen fuel process (HVOF), an 200–300 μm thermally insulating ceramic top

coat produced by means of APS or electron beam physical vapor deposition (EB-PVD) onto the bond coat, and thermally grown oxides (TGO) that can provide strong insulated ability of oxidation and corrosion resistance at the interface between the bond coat and the top coat during thermal exposure [2–4].

The degradation mechanism of TBCs and the prediction of the service life are usually such difficult complex problems that many researchers attempt to combine the results of numerical simulation with the rules from the experimental results. The initiation and the propagation of microcracks often rely heavily on the stress distribution in TBCs system, which is usually simulated by the Ansys or Abaqus software, while the regular failure region in TBCs system can be found from the experimental results such as isothermal oxidation exposure and the thermal cycling testing. Therefore, it is considerably crucial to fully understand the relationship between the state of stress in TBCs and its failure mechanisms. In general, the

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macro residual stress from the thermal mismatch between the ceramic coat (including TGO and top coat) and metallic bond coat will form the initial vertical microcracks from the surface of the ceramic top coat; while the local micro-thermal stress can be attributed to the oxidation of aluminum in bond coat due to the volume difference as well as the impoverished aluminum element in the bond coat and the subsequent unstable TGO growth [5]. Furthermore, the undulation morphology of TGO is often formed in TBCs system due to the different thermal expansion coefficient between the top coat ($\alpha_{YSZ} \approx 10.5 \times 10^{-6}$ m/K) and the TGO ($\alpha_{TGO} \approx 8.0 \times 10^{-6}$ m/K) and the bond coat ($\alpha_{BC} \approx 12.3 \times 10^{-6}$ m/K), and the presence of the non-protective oxides (CSN oxides: Co_3O_4 , Spinel and NiO) formed in TGO will weaken the TC/TGO interface. The non-protective CSN oxides in TGO, the change of the stress distribution, and the crack initiation and propagation in top coat and TGO can be regarded as the most critical factors regarding the degradation mechanisms of TBCs. Recently, more and more experimental results and numerical simulations show that the TGO layer in TBCs system can be generally divided into the parabolic growth of alumina and the linear growth of non-protective oxides respectively, and the non-protective oxides in TGO will significantly accelerate the failure of TBCs system. Therefore, a layer of homogeneous and pure alumina at the interface between top coat and bond coat can provide not only protective barrier for the metallic part of TBCs but also good adhesion at the interface of TGO/TC, indirectly prolonging the lifetime of TBCs during thermal exposure. However, the spallation of TBCs is strongly dependent on both the growth-stress and the thermal-stress in TGO [6–9] and the propagation of vertical surface cracks and the horizontal cracks in the topcoat [10–12]. Previous study suggests that the degradation of TBCs produced by APS process often arises from the unevenly distribution of the thermal stress within the undulated TGO at the interface between the bond coat and top coat [13]. According to the previous study, the residual stress, steady state energy release rate G_{SS} , the undulated morphology of TGO and the wavy value of G_{SS} have rather complex connection, resulting in the formation and propagation of the local cracks in the ceramic top coat that can absorb highly dense energy and indirectly improve the toughness of top coat [14]. The length (L) and density (ρ) of the vertical surface cracks have significant influence on the value of G_{SS} . The degradation mechanisms of TBCs induced by weakened TGO area would be replaced by other mechanisms when the density of vertical surface crack grew higher [15]. The vertical surface cracks do not propagate to the interface of TGO/TBC until its value of G_{SS} reaches to maximum. Furthermore, the stress field of the vertical surface cracks change substantially because the phase transformations take place in TGO, and this indirectly raise the growth driving force of the vertical surface cracks [16].

The presence of the CSN oxides can be the most critical factor that is closely related to the degradation of TBCs and deteriorate the state of the stress in TGO, but it cannot be easily simulated by simulation software as the stress distribution in TBCs [17]. Thus, this paper attempts to analytically and numerically explain the relationships between the formation and growth of TGO and the propagation of vertical surface cracks and horizontal cracks in top coat during the thermal cycling testing based on the experimental

measurement of the residual stress and the calculation of the steady state energy release rate G_{SS} within TGO.

2. Experimental details

The nickel-based superalloy Inconel-718 (The chemical composition are listed in Table 1) disks ($\Phi 25.4$ mm \times 3 mm) were used for the substrate, and a grit blasting machine was employed to roughen the surface of the substrate for the purpose to improve the adhesion between the substrate and the bond coat (the pressure of grit blasting: 0.8 MPa, angle: 80–90°, size of sand: 150–180 μm corundum sand). Subsequently, the substrates were cleaned by a mixture of absolute ethyl alcohol and acetone solution. The high velocity oxygen fuel process self-developed by thermal spraying laboratory of Tianjin University was used for spay deposition process (TJ9000 system, Tianjin University, China) of the bond coat, and the MCrAlY (Amdry 9951) powder size range of -37 ± 5 μm supplied by Sulzer Metco Inc. was used as the feedstock. The nominal composition of Amdry 9951 and the process parameters are listed in Tables 1 and 2(a) respectively. Finally, in order to prepare the top coat, the 8wt.% yttria stabilized zirconia (Sulzer Metco 204B-NS, HOSP™, particle range: -75 ± 45 μm , USA) commercial powder supplied by Sulzer Metco was deposited by APS facility (Sulzer Metco 9MC, Westbury, NY-USA) which was programmed and performed automatically using the ABB robot. The APS parameters are listed in Table 2(b). Afterwards, the high vacuum sintering and heat treatment furnace (VHS-8812, Shenyang Jiayu Vacuum Technology Inc., China) (the limitation of vacuum degree: 2.6×10^{-3} Pa) was conducted at 1050 °C for 4 h, and the heat rate was set 8 °C/min from the room temperature. (Heating-up vacuum degree: 7×10^{-3} Pa, insulated vacuum degree: 3×10^{-3} Pa, temperature heating up speed: 8 °C/min). In order to modify the diffusion mechanisms of the aluminum element as well as intervene the formation and the growth of TGO, the specimens were heated isothermally within a furnace at (950 °C, 1000 °C and 1100 °C) for 10 h prior to thermal cycling testing. Subsequently, the specimens were marked respectively as below:

- No Vacuum pre-oxidation (N-VHT);
- Vac.(1050,4 h) (VHT);
- Vac.(1050,4 h) + 950,10 h (VHT 950);
- Vac.(1050,4 h) + 1000,10 h (VHT 1000);
- Vac.(1050,4 h) + 1100,10 h (VHT 1100).

The thermal cycling testing in this work was carried out to examine the durability of TBCs. And we used extreme conditions to accelerate the failure of TBCs, and the parameters are as follows: temperature 1050 °C, duration time 60 min, quenching water 25 °C. Afterwards, the specimens sectioned into small portions by the diamond saw machine were mounted in epoxy, which can ensure that the ceramic top coat remained intact. The FESEM (S-4800, Hitachi Inc., Japan) – a cold field emission electron microscope equipped with an EDS analyzer (INCA, Oxford Instrument Inc., England) was conducted to measure the TGO thickness (30 typical positions each specimen) and analyze the elements of TGO after thermal cycling testing. To characterize and identify the presence of

Table 1

Nominal chemical composition (wt. %) of Inconel 718 superalloy substrate and Amdry 9951 bond coat powder.

	Ni	Cr	Fe	Mo	Nb	Co	Mn	Si	Cu	Al	Ti	Y
Substrate	50–55	17–21	Bal.	2.8–3.3	4.75–5.5	1	0.35	0.35	0.3	0.2–0.8	0.7–1.15	–
Bond coat	32	21	–	–	–	Bal.	–	–	–	8	–	0.5

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