Glass–ceramics as oxidation resistant bond coat in thermal barrier coating system

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Abstract

Thermal barrier coating (TBC) system consisting of yttria stabilized zirconia (YSZ) top coat, glass–ceramic bond coat and nickel base superalloy substrate was subjected to static oxidation test at 1200 °C for 500 h in air. Oxidation resistance of this TBC system was compared with the conventional TBC system under identical heat treatment condition. Both the TBC systems were characterized by SEM as well as EDX analysis. No TGO layer was found between the bond coat and the top coat in the case of glass–ceramic bonded TBC system while the conventional TBC system exhibited a TGO layer of about 16 μm thickness at the bond coat-top coat interface region.
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1. Introduction

There is an ever-increasing demand of thermal barrier coating (TBC) for the thermal protection of nickel base superalloys used as gas turbine blades [1–2]. Generally, thermal barrier coating system is a three-layered structure of one ceramic top coat, an intermediate NiCoCrAlY/PtAl based metallic bond coat and a metallic substrate. The metallic bond coat is deposited between the metallic substrate and the ceramic top coat to protect the underlying metal from oxidation and high temperature corrosion and to enhance the adherence between the dissimilar substrate and top coat [3].

During service, oxidation of the bond coat at the high temperatures produces a thermally grown oxide (TGO) scale at the bond coat-top coat interface, which increases with increasing operation time. This phenomenon is considered to be the most significant factor in determining the lifetime of a TBC system [3–4]. High stresses are generated in the interface between the bond coat and the TGO due to oxide thickening (volume increase), thermal expansion misfit and applied loads.

Consequently, crack initiates and propagates leading to the spallation of the ceramic layer, which finally results catastrophic failure [3–4]. Therefore, formation of the TGO layer and its progressive thickening should be controlled to minimize the bond coat oxidation induced TBC degradation.

Present research activities are focused on understanding this predominant failure mechanism and to provide a probable solution of this problem. Chen et al. showed that heat treatment of the as sprayed TBC in a low pressure oxygen environment promoted the formation of a uniform, thin protective layer of alumina (Al$_2$O$_3$) at the bond coat-top coat interface and reduced the formation of some detrimental oxides such as Ni(Cr,Al)$_2$O$_4$ (spinel) and NiO during further thermal exposure in air [5]. Pre-oxidation surface treatment of the bond coat performed under specific condition decreased the TGO growth rate resulting in improvement in TBC life compared with a conventional TBC system [6]. Application of a platinum-modified aluminide coating between the CoNiCrAlY bond coat and the ZrO$_2$–Y$_2$O$_3$ top coat improved the oxidation resistance of the TBC system at the high temperatures [7]. Pint et al. found out that the lifetime of TBC can be improved by employing a more oxidation resistant bond coat [8]. The TBC life was significantly enhanced by the use of an intermediate Al$_2$O$_3$ diffusion barrier between the bond coat and the yttria stabilized zirconia top coat [9]. Functionally graded Al$_2$O$_3$–ZrO$_2$ thermal barrier coating

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was also found to decrease the oxidation rate of the TBC system [10].

In the present investigation, glass–ceramics was used as bond coat between the yttria stabilized zirconia (YSZ) top coat and the nickel base superalloy substrate. Experimental study was carried out to correlate the performance of this TBC system with the conventional TBC system in terms of oxidation resistance under identical heat treatment in air.

2. Experimental

YSZ ($8Y_2O_3$–$92ZrO_2$) and NiCoCrAlY (Ni–24Co–15Cr–8Al–1Y, in wt.%) were applied as the top coat and the bond coat, respectively on the nickel base superalloy (nimonic – AE 435) substrate by air plasma spraying technique with a METCO-F4 plasma gun. The nominal composition of the nimonic alloy substrate is given in Table 1. For the bond coating, the particle size was 20 ± 10 μm while the particle size of the top coating material was 35 ± 10 μm.

In the other case, glass–ceramics was applied as bond coat on the nimonic alloy substrate by the conventional enameling technique. Thereafter, 8 wt.% yttria stabilized zirconia was air plasma sprayed onto the glass–ceramic coated substrate. The bond coat material was prepared by melting the glass-forming batch at 1400 °C for 2 h, which was then fritted. The approximate oxide composition of the enamel frit was as follows: SiO_2 40–45; BaO 40–45; CaO 2–6; MgO 2–3; ZnO 2–8; MoO_3 2–8 in wt.%. The frit was further crushed to powder. The glass powder was wet milled along with various mill additions such as fume silica 3.0–5.0 (wt.%); washed Cr_2O_3 4.0–5.0 (wt.%); cobalt oxide 0.3–0.5 (wt.%) in a porcelain ball mill for about 48 h to obtain glass particles of 3–5 μm size, which was converted into slurry for application over the cleaned metal surface. The metal surface was thoroughly prepared by thermal degreasing and sand blasting followed by ultrasonic cleaning to achieve proper bonding of the coating with the metal. The coating material was applied on the cleaned metal substrate by the conventional spraying technique using a spray gun. The glass powder coated substrates were dried at 100 °C for 45 min and subsequently fired at 1200 °C for 5 min in a muffle furnace. Further, the glass coating was heat-treated for 1 h at 1000 °C to develop tiny crystals of barium magnesium silicate as the major phase along with barium silicate in the glass matrix.

Table 1
Nominal composition of nimonic alloy (AE 435)

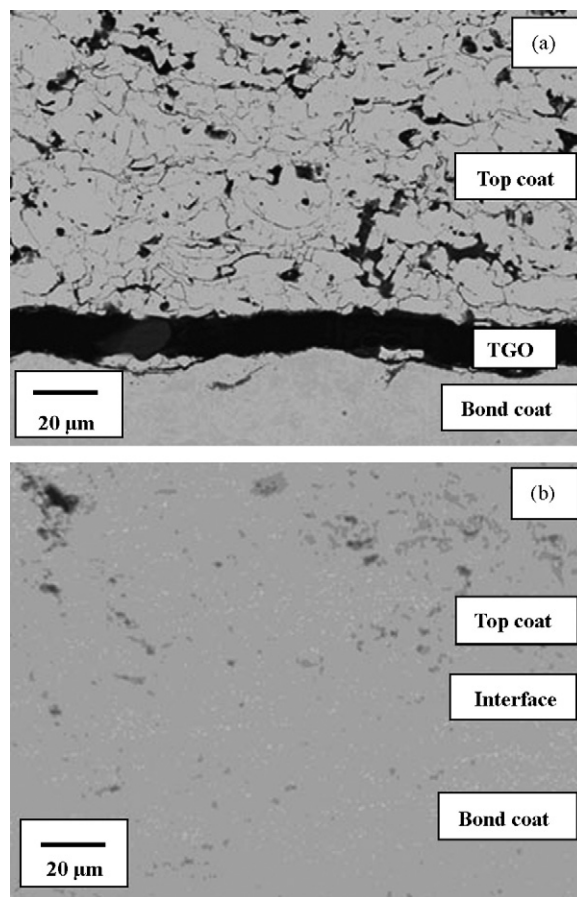| Elements	wt. %
Cr	19–22
Fe	1.0
C	0.12
Si	0.8
Mn	0.7
Ti	0.15–0.35
Al	0.15
Cu	0.07
S	0.01
P	0.015
Ni	Balance

Fig. 1. SEM micrographs showing (a) TGO layer between NiCoCrAlY bond coat and YSZ top coat and (b) absence of TGO layer between glass–ceramic bond coat and YSZ top coat.

In the both cases, bond coat thickness and top coat thickness were maintained to about 100 ± 10 μm and 400 ± 15 μm, respectively. Finally, static oxidation test of both the TBC systems was conducted at 1200 °C for 500 h in a muffle furnace in air. Five identical samples were used in each experiment.

The heat-treated TBC systems were characterized by scanning electron microscopy (SEM, LEO S430i, LEO, UK)
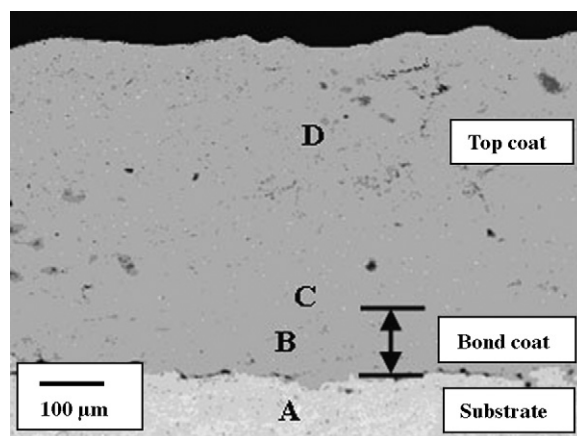

Fig. 2. Cross-sectional microstructure of a TBC system having YSZ top coat, glass–ceramic bond coat and metal substrate (A – substrate region; B – glass–ceramic bond coat region; C – glass–ceramic bond coat – YSZ top coat interface region; D – YSZ top coat region).

followed by energy dispersive X-ray (EDX, SiLi Detector) analysis.

3. Results and discussion

3.1. Microstructure of coatings

SEM studies on the cross-sections of five identical samples revealed that TGO layer of about $16 \pm 2 \mu m$ thickness was developed between the bond coat and the top coat in the case of TBCs having NiCoCrAlY bond coat and YSZ top coat. Fig. 1a illustrates the typical SEM micrograph showing TGO layer between the YSZ top coat and the NiCoCrAlY bond coat. On the contrary, cross-sectional examinations of another five identical samples displayed no TGO layer between the top coat and the bond coat wherein the TBCs were composed of YSZ top coat and glass–ceramic bond coat. Furthermore, there was

no distinct interface between the bond coat and the top coat, which indicates better structural integration of the TBC system. Typical SEM microstructure has been shown in Fig. 1b. Since the glass–ceramic material is basically oxide based, bond coat oxidation did not occur. Hence, TGO layer was not appeared at the bond coat-top coat interface region. In addition, the inherent lower thermal conductivity and higher oxidation resistance of the glass–ceramic based bond coat decreased the substrate temperature and protected the metal component from oxidation as can be seen from Fig. 2.

3.2. EDX analysis

The elemental composition analysis of the TGO layer showed the presence of aluminium and oxygen in all the samples, which implies that the TGO layer is made of aluminium oxide. Researchers have already established that Al_2O_3 is predomi-
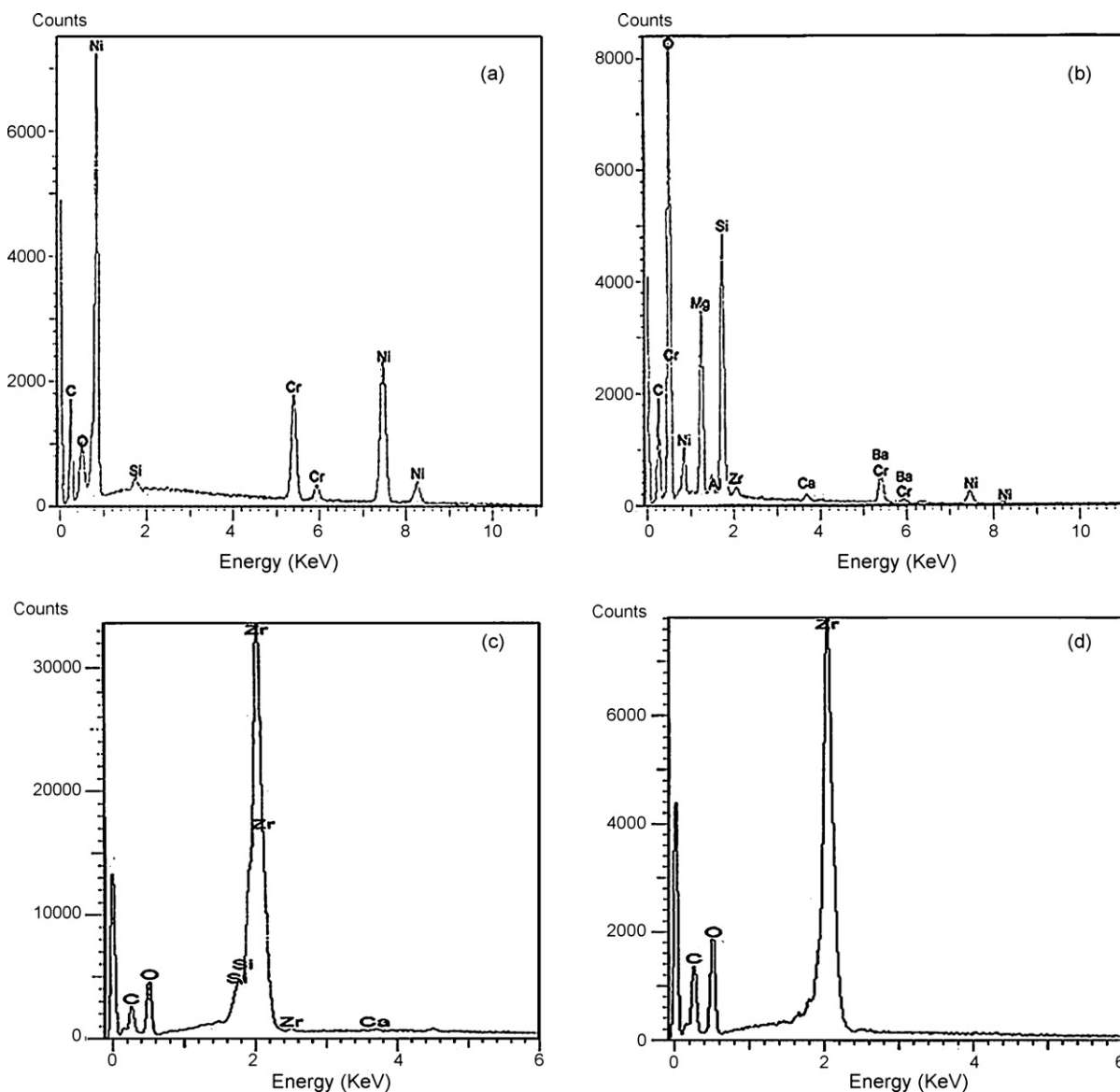

Fig. 3. EDX analysis of (a) substrate; (b) glass–ceramic bond coat; (c) bond coat-top coat interface and (d) YSZ top coat at the regions identified as A, B, C and D in Fig. 2.

nantly formed between the bond coat and the top coat during thermal exposure of the conventional TBC system with NiCoCrAlY bond coat [3–4]. EDX analysis (Fig. 3) was also performed over the cross-section of the TBC system (Fig. 2) at some regions indicated as A, B, C and D. It detected the presence of Ni, Cr, Si, O elements (Fig. 3a) in the substrate (region A of Fig. 2). In the glass–ceramic bond coat (region B of Fig. 2), Ba, Mg, Si, Ca, O, Ni, Cr, Al, Zr elements were found (Fig. 3b). The bond coat-top coat interface (region C of Fig. 2) showed the presence of Zr, O, Si, Ca elements (Fig. 3c) whereas only Zr, O elements were identified (Fig. 3d) in the top coat (region D of Fig. 2). This analysis technique confirmed that no new phase was developed between the bond coat and the top coat of the TBC system even after prolonged oxidation treatment.

4. Conclusion

The present study suggests that the use of glass–ceramic based bond coat can eliminate the problem of metallic bond coat oxidation induced degradation of the TBC system. However, detailed investigation is required to evaluate the performance of this TBC system in actual or simulated service condition for optimizing the coating compositions to produce a reliable TBC system using glass–ceramics as bond coat.

Acknowledgements

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