Surface & Coatings Technology 284 (2015) 69–74

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Thermal durability of thermal barrier coatings with bond coat composition in cyclic thermal exposure

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ARTICLE INFO

Article history:
Received 1 April 2015
Revised 1 August 2015
Accepted in revised form 2 August 2015
Available online 17 August 2015

Keywords:
Thermal barrier coating
High-velocity oxy-fuel
Bond coat composition
Feedstock powder
Thermal durability

ABSTRACT

The effects of bond coat composition on the microstructure evolution and thermal durability of thermal barrier coating (TBC) were investigated through cyclic thermal exposure. The microstructure of the bond coat was controlled using various feedstock powders, such as NiCrAlY, NiCoCrAlY, and CoNiCrAlY, which were coated on the Ni-based substrate using a high-velocity oxy-fuel process. The top coat was prepared with high purity feedstock powder (METCO 204 C-XCL) using an air plasma spray (APS) process. The thermal durability of the TBCs was evaluated through the cyclic thermal fatigue (CTF) and thermal shock (TS) tests, including the microstructure evolution, the thermally grown oxide (TGO) growth behavior, and thermomechanical properties. After the CTF and TS tests, the TBC with the Ni-based bond coat showed a longer lifetime performance and less degradation in hardness value than those with the Ni–Co- and Co–Ni-based bond coats. The results indicate that the bond coat composition produce an obvious effect on the thermomechanical properties of the TBC system. The relationship between bond coat composition and thermal durability is extensively discussed, based on the microstructure evolution and element diffusion behavior.

1. Introduction

Thermal barrier coating (TBC) has been extensively employed to improve the fuel efficiency of gas turbines and to allow higher operating temperatures or longer lifetime performance of components. Therefore, these coatings should protect metallic components because their lifetime performance is degraded as a result of corrosion, oxidation, and/or excessive heating loads during service in thermally extreme environments. Yttria-stabilized zirconia ceramic coating has good thermal stability and wear resistance at high temperatures. Thus, an isolation layer of 250 μm for TBC can reduce the surface temperature of turbine components by as much as 170 °C [1,2]. These days, the working temperature of gas turbines is increasing to 1600 °C to increase the thermal efficiency of gas turbine engines in power generation [3–6]. Apart from oxidation resistance, metallic bond coats can offer improved adhesion between substrate and top coat to withstand the residual and/or thermal stresses caused by thermal expansion mismatch during service. In addition, the thermal durability of the TBC system is closely related to the interface properties between the bond and top coats. The thermal and residual stresses created in heating and cooling in thermal cycling, respectively, and the growth of a thermally grown oxide (TGO) layer can lead to TBC failure [7,8]. Some studies used to include the TGO as a part of the system despite it being a reaction product that forms because of bond coat oxidation as oxygen ingresses through the interconnected pores of the top coat [9–12].

Two general methods used to apply the ceramic layer (top coat) are electron beam physical vapor deposition (EB-PVD) and air plasma spray (APS), which latter is the lower-cost alternative [9]. However, it is difficult and very expensive to make thick coatings using the EB-PVD process. In addition, bigger equipment and higher power are necessary. Therefore, the APS process is the more commercial method because of lower cost and lower thermal conductivity. For the past several years, the development of bond coats using the high-velocity oxy-fuel (HVOF) process has been gaining attention, and several articles have highlighted the significance of HVOF bond coats for TBC applications [13–16]. The HVOF bond coats have a higher density, superior mechanical properties, and lower surface roughness compared with those deposited using the APS process. Notably, fracture surfaces of the HVOF coats revealed a more homogeneous structure [7]. Using the HVOF technique to prepare bond coats, it is assumed that a high thermal durability and a better stability should be achieved [17]. Because of its outstanding resistance to oxidation and corrosion, there is a wide range of metallic alloys used as bond coats, normally consisting of a MCrAlY alloy, where M stands for nickel (Ni), cobalt (Co), or a combination of them. The characteristics of Ni are high corrosion resistance and high melting point; Co can give

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http://dx.doi.org/10.1016/j.surfcoat.2015.08.030
0257-8972/

temperature stability, corrosion, and wear resistance; Cr can improve hot-corrosion resistance; Al can improve ductility, determining oxidation degree related with TGO; and Y can improve adherence to the oxide layer. The Co–Ni-based bond coat and Ni–Co-based bond coat are widely used because of their superior thermomechanical properties [1,3,18,19]. Usually, the bond coat of a TBC system employed at high temperature involves Co because of the high-temperature oxidation resistance, thus enhancing the cycle life of TBCs [19]. Even though the working temperature of gas turbines is over 1600 °C, the temperature of components, such as blade and vane, is still in the range of 950–1100 °C in real environments, owing to the improvement of cooling system. Therefore, the thermal durability of TBCs with Co additive bond coats should be analyzed in the working condition, such as 950–1100 °C, which has not been studied yet.

In the present study, three kinds of feedstock powder, namely Co–Ni-based, Ni–Co-based, and Ni-based powders, were employed for the bond coats, which were coated using the HVOF process. The effects of the feedstock species in the bond coat on the thermal durability of TBC systems were investigated through the cyclic thermal fatigue (CTF) and thermal shock (TS) tests, including the microstructure evolution and TGO growth behavior of each TBC system.

2. Experimental details

2.1. Preparation of TBC specimens

Three types of commercially available powder were used as the HVOF feedstock. A nickel-based directionally solidified superalloy was used as a substrate, which has the following nominal composition by weight: 65.0Ni–10.0Cr–7.5Ta–7.0W–5.0Al–4.4Co–1.0Ti–0.08C–0.01Zr–0.01B. The dimensions of the specimens were 25 μm in diameter and 5 μm in thickness. The substrate was sandblasted using an alumina powder with particle size of 60 mesh, and then the HVOF process using Diamond Jet-2600 DJM (Plasma Technik) was conducted within 2 h. Three kinds of feedstock powder with different compositions were used for the bond coat that was coated on the substrate: AMDRY 9951 (Sulzer Metco Holding AG, nominal composition of Co–32Ni–21Cr–8Al–0.5Y in wt.% and particle size of 5.5–38 μm), AMDRY 997 (Sulzer Metco Holding AG, nominal composition of Ni–23Co–20Cr–8.5Al–4Ta–0.6Y in wt.% and particle size of approximately 37 μm), and AMDRY 9624 (Sulzer Metco Holding AG, nominal composition of Ni–22Cr–10Al–1.0Y in wt.% and particle size of approximately 11–37 μm). A ceramic top coat was coated on the bond coats by the APS using METCO 204 C-XCL (Sulzer Metco Holding AG, Switzerland, 8 wt.% Y_2O_3 doped in ZrO_2, particle size of 45–140 μm). The thicknesses of the bond and top coats were approximately 250 μm and 550 μm, respectively. Detailed spray parameters for the HVOF and APS processes are shown in Table 1, with modifications to the manufacturer's specifications.

2.2. Cyclic thermal fatigue and thermal shock tests

A bottom-loading programmable cyclic furnace was used for determining life performance of the TBC systems. The CTF tests were performed for 1430 cycles at a surface temperature of 1100 °C with a temperature difference of 150 °C between the top and bottom surfaces of the specimen with a dwell time of 40 min, and then natural air cooling was allowed for 20 min at room temperature. The failure criterion was defined as 25% buckling or spallation of the top coat in the CTF tests. The TS tests were carried out for 300 cycles in a box-type furnace. When the temperature of the furnace reached 1100 °C, specimens were put into the furnace. In the TS, specimens were held for about 40 min in the furnace and then directly quenched in water. Throughout the TS, the temperature of the water was between 20 °C and 35 °C. More than 50% of the spalled region in the top coat or cracked at the interface between the top and bond coats was adopted as the criterion for failure in the TS tests [20]. Minimum three runs were performed to obtain reliable lifetime performance of TBC specimens in both tests.

2.3. Characterization

The selected TBC specimens were preprocessed to observe the cross-sectional microstructure and measure the mechanical properties before and after the CTF and TS tests. The specimens were mounted with a fluid epoxy resin, polished using silicon carbide paper, then final polishing using 3 μm and 1 μm diamond pastes. The cross-sectional microstructure of TBC specimens was observed using a scanning electron microscope (SEM, JEOL Model JSM-5610, Japan). The hardness values of bond coats were determined using a micro-indenter (HM-114, Mitutoyo Corp., Japan) with a Vickers tip for a load of 3 N and holding of 15 s. To obtain reliable values, more than 10 points were tested for each result. The size of the indentation impression was measured using SEM and all indentations were performed at room temperature. The standard test method for Vickers Indentation Hardness of Advanced Ceramics (ASTM C1327-03) was employed for the hardness measurement in this study. The chemical composition of each TBC system after cyclic thermal exposure was determined using an energy dispersive spectrometer (EDS, JEOL Model JSM-5610, Japan).

3. Results and discussion

3.1. Microstructure of as-prepared TBCs

The cross-sectional microstructures for as-prepared TBCs are shown in Fig. 1, showing bond coats prepared with different feedstock powders (AMDRY 9951, AMDRY 997, and AMDRY 9624) using the HVOF process. The top coats prepared using the APS process showed typical microstructures with horizontal 'splat' boundaries/cracks, pores, and unmelted powder. In Fig. 1, the TBCs did not show any delamination or cracking at the interface between the top and bond coats. All specimens showed an irregular surface roughness at the interface. The bond coats prepared using the HVOF exhibited a dense microstructure, and the interface between the substrate and the bond coats also showed a sound condition.

METCO 204 C-XCL feedstock powder has a better sintering resistance at service temperatures above 1300 °C than other commercial feedstock powders, such as METCO 204 C-NS, METCO 204 NS-G, and METCO 204 NS because METCO 204 C-XCL has a high purity, compared with commercial feedstock powders with standard purity. These characteristics promise better mechanical properties and a superior thermal stability. Shrinkage, known as an indicator of coating degradation

Table 1
Feedstock powders and coating parameters for preparing the bond and top coats.

Item	Feedstock	Feeding rate	Gun distance	Gun speed	Step distance	Carrier gas	Flow rate
Bond coat (HVOF)	AMDRY 9951 AMDRY 997 AMDRY 9624	40 g/min	200 mm	700 mm/s	4 mm	Air O_2 H_2	42 NLPM 12 NLPM 62 NLPM
Top coat (APS)	METCO 204 C-XCL	45 g/min	110 mm	500 mm/s	5 mm	H_2 Ar	27 NLPM 96 NLPM