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ScienceDirect
Trans. Nonferrous Met. Soc. China 24(2014) s29−s35
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Thermal stability and mechanical properties of thick thermal barrier coatings with vertical type cracks

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Received 18 June 2013; accepted 25 October 2013

Abstract: The thermal stability and failure mechanism of thick thermal barrier coatings (TBCs) with and without vertical type cracks were investigated through the cyclic thermal exposure and thermal-shock tests. The TBC systems with thickness of about 2000 μm in the top coat were prepared by an air plasma spray (APS) on the bond coat of about 150 μm in thickness prepared by APS. The adhesive strength values of the as-prepared TBCs with and without vertical type cracks were determined to be 24.7 and 11.0 MPa, respectively, indicating the better interface stability in the TBC with vertical type cracks. The TBC with vertical type cracks shows a better thermal durability than that without vertical type cracks in the thermal cyclic exposure and thermal-shock tests. The hardness values of the as-prepared TBCs with and without vertical type cracks were found to be 6.6 and 5.3 GPa, respectively, which were increased to 9.5 and 5.5 GPa, respectively, after the cyclic thermal exposure tests. These results indicate that the vertical type cracks developed in the top coat are important in improving the lifetime performance of thick TBC in high temperature environment.
Key words: thermal barrier coating; air plasma spray; vertical type crack; thermal durability

1 Introduction

Thermal barrier coatings (TBCs) are extensively employed in high temperature components of gas turbines, such as turbine and combustion, to increase the turbine inlet temperature, hence increasing the efficiency and performance of gas turbines [1]. TBCs can be considered a four-layered material system, consisting of the following aspects: 1) a substrate of nickel- or cobalt-based superalloy; 2) an oxidation-resistant metallic bond coat of MCrAlY formed by the air plasma spray (APS), vacuum plasma spray, and high velocity oxygen fuel (HVOF) methods; 3) thermally grown oxide (TGO) layer, typically *α*(Al) or spinel structure oxide, formed during heat treatment or in service; and 4) a ceramic top coat of 6%−8% (mass fraction) yttria-stabilized zirconia deposited by either APS or electron beam-physical vapor deposition processes [2,3]. There are three ways to enhance TBC performance, specially focused on the thermal conductivity of TBC: 1) developing feedstock powder with a low thermal conductivity; 2) controlling porosity of the top coat; and 3) increasing thickness of the top coat. Many factors, such as high melting point, thermal stability, low thermal conductivity, chemical inertness, good adhesion with the metallic substrate, low sintering rate, and thermo-mechanical properties, have to be considered for practical applications of TBCs. The increase in thickness of the top coat reduces the surface temperature of cooled components in gas turbine engines at the rate of 4−9 °C per 25.4 μm [4]. The vertical type crack increases the strain tolerance of TBC system and also reduces the thermal and residual stresses caused by the difference in thermo-mechanical properties between the top and bond coats [5−9]. Therefore, the vertical type crack is potential in improving the thermal-shock resistance and thermal durability, which should be employed in thick TBC [10].

Therefore, the present work dealt with the thermo-mechanical properties of the thick TBCs with

Foundation item: Project (2011-0030058) supported by the National Research Foundation of Korea (NRF) Funded by the Korean Government (MSIP); Project (20134030200220) supported by the Human Resources Development Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) Funded by the Korea Government Ministry of Trade, Industry and Energy and by the Korea Institute of Materials Science (KIMS) in 2013
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DOI: 10.1016/S1003-6326(14)63284-2

and without vertical type cracks, as a new strategy for the advanced TBC system. The microstructure evolution and thermal durability of the thick TBCs with and without vertical type cracks were investigated through the cyclic thermal exposure and thermal-shock tests, including the effect of vertical type cracks created on the top coat on the delamination behavior or fracture behavior of thick TBC system. In addition, the relationship between the thermal durability and vertical type cracks was established based on the microstructure, adhesive strength, and hardness variation before and after the cyclic thermal exposure and thermal-shock tests.

2 Experimental

2.1 Preparation of TBC

The vertical-cracked TBCs employed in this study were prepared by a specialized APS coating system. A Ni-based superalloy was used as a substrate with the disk shape of 25.4 mm in diameter and 5 mm in thickness. The bond coat was coated on the substrates with about 150 μm thickness using a Ni-based intermetallic powder. The bond coats for the TBCs with and without vertical type cracks were prepared by the HVOF and APS coating systems, respectively. The top coat was coated on the bond coat with about 2000 μm thickness using a 7%−8% yttria stabilized zirconia powder. The fabrication parameters for the bond and top coats were recommended by manufacturers (Praxair Korea Co. Ltd. and Chrome-Alloying Co. Ltd.).

2.2 Microstructure and mechanical property

The selected specimens before and after the cyclic thermal exposure and thermal-shock tests were pre-processed to observe the cross-sectional microstructure and to evaluate the mechanical properties. The mounted specimens were given a final polish with diameter of 1 μm diamond paste. The cross-sectional microstructures of the TBC specimens were observed by a scanning electron microscope (SEM; Model JSM−5610, JEOL, Japan). The thickness of the TGO layer formed at the interface between the bond and top coats after the two tests was measured by SEM. The hardness values of the top coats before and after the tests were determined using a microindenter (HM−114, Mitutoyo Corp., Japan) with a Vickers tip for a load of 3 N, using the equation proposed by LAWN et al [11]. To obtain more reliable values, 15 points were indented for each result. Elemental analysis was performed for the TGO layer using energy dispersive X-ray analysis (EDX; S2700, Hitachi, Japan). The adhesive strength of each TBC was measured according to the ASTM standard (ASTM−C−633−01) [12]. The specimen for the adhesive strength test was prepared by bonding that to the jig fixture with an epoxy adhesive in the oven at 200 °C for 3 h.

2.3 Thermal fatigue and thermal-shock tests

A bottom-loading programmable cyclic furnace was used to determine the life cycles of TBC systems. The electric thermal fatigue (ETF) tests were performed for 1143 cycles at a surface temperature of 1100 °C with a temperature difference of 150 °C between the top and bottom surfaces of TBC specimen. In the ETF tests, the dwell time was 60 min and natural air cooling was allowed for 10 min at room temperature (25−30 °C), and the 25% buckling or spallation of the top coat was defined as a failure criterion. The TBC specimens in the ETF tests were removed at different fractions of their life for cross-sectional studies, while others were cycled until the failure criterion was met, to observe signs of failure. In the thermal-shock tests, when the furnace temperature reached 1100 °C, the specimens were placed in the furnace and held for 60 min, and then directly quenched in water for 5 min, the temperature of the water is about 20 °C throughout the tests. More than 50% buckling or spallation in the top coat was adopted as the criterion for failure. At least five specimens were tested for each condition [13−16].

3 Results and discussion

3.1 Microstructure of as-prepared TBCs

The cross-sectional microstructures of the as-prepared TBC specimens are shown in Fig. 1, which are the microstructures of the TBCs without and with vertical type cracks, respectively. The top coats are well deposited with the designed concept, without and with vertical type cracks. The thicknesses of the bond and top coats are (150±30) and (2000±100) μm (mean±standard deviation), respectively. The microstructures show intrinsic defects, such as pores, unmelted particles, splat boundaries, and oxide materials (Figs. 1(a_2) and (b_2)), as shown in the top coat prepared using a APS process. The length of vertical type cracks shown in Fig. 1(b_1) is determined to be (1201±521) μm. There are many horizontal cracks on both sides of each vertical type crack and its length is determined to be (83±25) μm. The microstructure of TBC specimen with vertical type cracks is denser than that without vertical type cracks, for developing vertical type cracks.

3.2 Cyclic thermal exposure

The cross-sectional microstructures of TBCs after cyclic thermal exposure are shown in Fig. 2. After the tests, the top coat with vertical type cracks is densified,