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Interfacial stability and contact damage resistance by incorporating buffer layer in thermal barrier coatings☆

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ABSTRACT

A buffer layer was introduced between the bond and top coats in air-plasma sprayed (APS) zirconia (ZrO_2)-based thermal barrier coating (TBC) system, to improve contact damage and interfacial stability. The microstructure is relatively continuous in the TBC system with the buffer layer, showing a step like distribution of Zr element between the top and bond coats. The TBC system with the buffer layer shows less strain than that without the buffer layer in the higher stress regions above about 1.3 GPa, while both TBC systems become soft by forming the top coat in the lower stress regions compared with the substrate. The TBC system with the buffer layer shows the lower stress–strain curves than that without the buffer layer in the thermal exposure with the relatively short dwell time of 1 h, showing the reverse trend with the relatively long dwell time of 10 h. Subsurface damage in the substrate is reduced at both indentation loads of $P = 500$ N and $P = 2000$ N by incorporating the buffer layer, independent of thermal exposure condition. The damage zone formed in the TBC system without the buffer layer increases with increasing exposure time, while the damage does not extend far in the case of the TBC system with the buffer layer. In fracture under contact environments, cracking or delamination is developed between the top coat and the buffer layer in the TBC system with the buffer layer, whereas the fracture is created at the interface of the bond coat and the substrate. The buffer layer is more efficient in protecting the substrate from contact environments and enhances the damage resistance of the TBC system.

1. Introduction

Plasma sprayed coating, especially air-plasma sprayed (APS) coating, is widely used to form protective coatings on metallic substrates. However, the high number of defects in APS coatings, such as pores, microvoids, unmelted oxides, and microcracks, limits the application of such coatings at the high working temperatures of gas turbines and diesel engines. The use of such coatings under these conditions will result in reduced service life [1–6]. Failure of an APS coating generally occurs by spallation of the coating at, or near, a thermally grown oxide (TGO) layer, which is created in service. The failure modes of APS coatings have been described in literature; failure depends on the thermal fatigue conditions, such as temperature and dwell time [2,6]. A mismatch of the thermal expansion between the ceramic coating and the metallic bond coating, and the high thermal stresses, are the other major factors leading to spalling of the coatings [7,8]. Normally, the reported compressive residual stresses on thermal barrier-coated high-pressure turbine blades are 2.4–2.8 GPa for the as-prepared coatings and 2.3–3.1 GPa after service, depending on the surface geometry of the TGO layer [8].

Many techniques have been developed in efforts to obtain a good microstructure and to enhance the adhesive strength, such as electron beam-physical vapor deposition (EB-PVD) and solution precursor plasma spray (SPPS) [2,9–12]. However, the APS coating with its economic benefits is still preferred commercially, in contrast to the use of the complex and expensive EB-PVD [1–3], although it has a low strain tolerance compared with coatings created by more advanced coating methods. In order to enhance the strain tolerance of the APS coating and to improve the adhesive strength between the top and bond coats, the microstructure

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or composition has been designed to reduce the discontinuity of the coefficient of thermal expansions between the top and bond coats and to minimize the residual stresses in the coating. This has resulted in functionally graded thermal barrier coating (TBC) systems [7,13–16]. Numerous factors, besides the thermo-mechanical properties, have to be considered in practical applications of TBC systems, such as erosion and wear resistance. There is therefore a need to improve the adhesive strength and mechanical characteristics, which are essential to improving the reliability and lifetime performance of the APS-coated TBC system.

In this study a buffer layer between the top and bond coats was introduced for commercial applications, comparing to the functionally graded TBC system. The new TBC system has a total of three coating layers on a metallic substrate, coated by the APS process. The most common or standard TBC system consists of two coating layers—a zirconia (ZrO_2)-based top coat and an intermediate bond coat on a metallic substrate. In order to determine and to understand the influence of the buffer layer on the stability of the interface and the fracture behavior, the damage resistance of the new TBC system with the buffer layer was evaluated using the Hertzian contact technique and compared with the common TBC system without the buffer layer. The effect of thermal exposure condition on the indentation stress–strain behavior was also investigated, and the contact damage related to the buffer layer and the thermal exposure condition indicated. Both sets of results obtained from the TBC systems without and with the buffer layer, respectively, were compared.

2. Experimental procedure

2.1. Materials

A nickel–chromium alloy (Nimonic 80A, nominal composition Ni–20Cr–2.3Ti–1.2Al–3.0Fe–0.1C–1.0Mn–1.0Si, in wt.%) was used as a substrate. The APS process was used to prepare a Ni–Co–Cr–Al–Y alloy (nominal composition Ni–17.5Cr–5.5Al–2.5Co–0.5Y_2O_3, in wt.%) bond coat (METCO 461NS, Sulzer Metco Holding AG, Switzerland) on the substrate, with a thickness of $d = 100 \pm 25\,\mu m$. The top coat was formed using powdered ZrO_2 containing 8 wt.% yttria (Y_2O_3) (METCO 204C-NS, Sultzer Metco Holding AG, Switzerland), which was also air-plasma sprayed, with a thickness of $d = 200 \pm 40\,\mu m$, onto two different samples—one with and one without a buffer layer. The buffer layer was introduced between the bond and top coats. It was also air-plasma sprayed, with a thickness of $d = 50 \pm 20\,\mu m$, onto the bond coat. Blended powders of 65% magnesium zirconate ($MgZrO_3$) and 35% nickel–chromium alloy (Ni–Cr) (METCO 303NS, Sultzer Metco Holding AG, Switzerland) were used. Each coating process was carried out using a recommended gun (Metco 9MB), according to the manufacturer's specifications. The thermal exposure tests were performed at 1210 °C, with dwell times of 1 h till 25 cycles and 10 h till 5 cycles in the furnace specially designed—one side of the sample was exposed and the other side open to air.

2.2. Characterization

The samples with and without the buffer layer prepared by the APS process were sectioned and polished with a 1 μm diamond paste in order to observe the cross-sectional microstructures of each TBC system. Observations were carried out using a scanning electron microscope (SEM, JEOL Model JSM-5610, Japan). Line mapping for the elements comprising each TBC system was conducted using an energy-dispersive X-ray spectrometer (EDS, S2700, Hitachi, Japan).

Indentation stress–strain curves were obtained by recording indentations on the surfaces of the TBCs before and after the thermal exposure. Tungsten carbide (WC) spherical indenters with radii of $r = 1.98$–7.83 mm (J & L Industrial Supply Co., MI, USA) and a mechanical testing machine (Instron Model 8500, Instron Corp., Canton, MA, USA) were used. Samples with the bond coat alone were prepared by grinding and polishing the TBCs after the thermal exposure. The thin bond coat was about 50 μm and the thick one was about 100 μm. The substrate after the thermal exposure was prepared by the same method as used for the bond coat. For the indentation tests, the top surface was slightly polished, followed by polishing with a 1 μm diamond paste. In order to determine the damage resistance of each TBC system, bonded-interface samples (polished on both sides) of both with and without the buffer layer, before and after the thermal exposure, were prepared by sticking them together with superglue and then clamping them [17–19]. The interface thickness was less than 5 μm. Single indentations were made on the top surfaces of the samples using the WC spherical indenter with a radius of $r = 3.18$ mm at peak loads of $P = 500$ N and $P = 2000$ N, using the mechanical testing machine. The indentations were made along the trace of the bonded interface on the top surface. The indented samples were then separated and cleaned, and viewed using an optical microscope in the Nomarski interference contrast mode. All the experiments were performed in air at room temperature.

3. Results and discussion

3.1. Microstructure

The as-prepared microstructures of both TBC systems with and without the buffer layer and the line mapping results for each element comprising the TBCs are shown in Fig. 1. In the TBC system without the buffer layer the interface between the top and bond coats exhibits a discontinuous microstructure, which is confirmed by the distribution of elements. The elemental zirconium (Zr) suddenly disappears, passing the interface between the top and bond coats. In the TBC system with the buffer layer the microstructure is relatively continuous and the Zr can be seen in some regions between the top and bond coats, including Ni, Cr, Mg elements. The buffer layer comprising 65% $MgZrO_3$ and 35% Ni–Cr ensures a sound bonding between the top and bond coats and offers a great potential for better service performance due to the stability at the interface.

3.2. Indentation stress–strain behavior

Indentation stress–strain behaviors for each TBC system without and with the buffer layer, i.e., the 2- and 3-layer coatings, and the substrate are shown in Fig. 2(A), and the substrate with the bond coat only and the substrate alone after the thermal exposure are shown in Fig. 2(B) as functions of bond coat thickness and thermal exposure condition. The stress–strain curves of the TBC systems are much lower than that of the substrate in lower stress regions, resulting in a 'softening' of the substrate. This is due to the lower elastic modulus (E) value of the top coat, caused by defects such as pores and microcracks in the top coat. In higher stress regions, the stress–strain curve of the TBC system with the buffer layer is slightly higher than that of the substrate, whereas the curve of the system without the buffer layer is still lower. This result indicates that the buffer layer acts in higher stress regions and the stress–strain curves in lower stress regions are affected by the top coat. While the stress–strain curves are not affected much by a change in the bond coat thickness, a minor effect on the 'softening' of the substrate is observed in lower stress regions, as shown in Fig. 2(B). This is in