Journal of Alloys and Compounds 584 (2014) 19–27

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

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

Residual stress evolution of thermally grown oxide in thermal barrier coatings deposited onto nickel-base superalloy and iron-base alloy with thermal exposure ageing

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ARTICLE INFO

Article history:
Received 20 May 2013
Received in revised form 6 August 2013
Accepted 24 August 2013
Available online 31 August 2013

Keywords:
Nickel-based superalloy
Iron-based alloy
Thermal barrier coatings
Phase transformation
Undulated TGO
Compressive residual stress

ABSTRACT

The objective of this work is to understand the influences of different chemical compositions of iron-based and nickel-based substrates on the TGO growth rate, the distribution of residual stress in TGO, the Quantity of the Spinel Cap Presence (QSCP) at the convex of undulated TGO, as well as the θ-Al_2O_3 to α-Al_2O_3 phase transformation. A thermal barrier coatings (TBCs) system consisting of the NiCrAlY bond coat and the 8YSZ topcoat (500 μm thickness) were successfully produced onto the substrates of nickel-based superalloy and iron-based alloy by atmospheric plasma spraying (APS), respectively. The results suggest that, compared with the iron-based substrate, both the TGO growth rate and the aluminum depletion in the bond coat with the nickel-based substrate develop significantly slower as the thermal exposure proceeds. It is proposed that the Cr^{3+} and Al^{3+} with small radii may considerably influence the mechanisms of phase transformation in the TGO, and these small ions can promote the θ-Al_2O_3 to α-Al_2O_3 phase transformation. Furthermore, the TBCs system with iron-based substrate was prone to have much shorter stage of θ-Al_2O_3 to α-Al_2O_3 phase transformation and a dramatic reduction of θ-Al_2O_3 content in the TGO, which had indirect effect on the thermo-dynamic behavior of TGO during the subsequent stage of isothermal oxidation. Furthermore, the apex of the convex of undulated TGO usually has the largest compressive residual stress. The spinel oxides can be inclined to form at the apex region of the convex of the undulated TGO with a lower value of b/a geometric parameter. However, only few spinel oxides appeared at the flank region of the convex. Nevertheless, the 'spinel cap' feature usually formed at the area of the apex and the flank of the convex of undulated TGO with a higher value of b/a geometric parameter. Compared with the nickel-based substrate, the more presence of 'spinel cap' at the area of the convex of undulated TGO with a iron-based substrate can be found at the convex of undulated TGO, and its earlier end of the θ-Al_2O_3 to α-Al_2O_3 phase transformation may result in the lower value of compressive residual stress in average.

1. Introduction

Thermal barrier coatings (TBCs) are widely used for hot components (such as blades, vanes and combustion chambers) of land-based gas turbine and aero-engine to protect high temperature oxidation and corrosion [1–3]. Conventional TBCs system usually consists of a ~150 μm MCrAlY (M represents Ni, Co or Ni & Co) bond coat deposited using plasma spraying (APS, LPPS, or VPS) or high velocity oxygen fuel (HVOF), a ~250 μm thermally insulating ceramic topcoat produced by atmospheric plasma spraying (APS) or electron beam physical vapor deposition (EB-PVD) onto the bond coat, and thermally grown oxides (TGO) that can provide strong ability of oxidation and corrosion resistance at the interface between the bond coat and topcoat during the thermal exposure service [3,4–6].

A ~250 μm topcoat can provide 110–170 K thermally insulation to vanes and blades of gas turbine engines [7], resulting in an improved component durability under the state of the current blade cooling technology. In order to enhance the efficiency of gas turbine engines, the gas turbine inlet temperature should increase. The efficiency of gas turbine can be improved remarkably using thick TBCs compared with conventional TBCs, indirectly reducing an amount of cooling air required by hot components, which is responsible for the fuel-consumption of turbine engine system [8,9]. For most applications, it is well established that the topcoat of TBCs is below 500 μm owing to their limited reliability currently. As the increase of the thickness of TBCs, the thermal stress between the topcoat and metallic substrate can be noticeably enhanced, which would result

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http://dx.doi.org/10.1016/j.jallcom.2013.08.144

Table 1
Chemical composition (wt.%) of Inconel 718 superalloy substrate and Amdry 962 bond coat powder.

	Ni	Cr	Fe	Mo	Nb	Co	Mn	Si	Cu	Al	Ti	Y
Inconel 718	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	Bal.	22	–	–	–	–	–	–	–	10	–	1

in TBC spallation in gas turbines [10,11]. Nevertheless, the defects such as pores and microcracks produced by means of controlling the plasma spraying parameters can be increased considerably in thick TBCs. Thus, the potential thermal insulation and mechanical properties such as thermally insulated resistance, strain tolerance, elastic strain energy and energy release rate can be modified correspondingly [12,13].

Land-based gas turbine engine usually performs in the state of continuous service for tens of thousands of hours, which is considerably different from the gas turbine aero-engines. This is owing to part of components of land-based gas turbine are usually made of iron-based alloy, most importantly they are often under the state of continuous operation but the abrupt brake occurs rarely in its service. Atmospheric plasma spraying can be regarded as a common deposition facility with the advantages of high deposition efficiency and lower-cost running compared with EB-PVD process. A micro-thermal stress (phase transformation of thermally grown oxides and topcoat) and a macro-stress (thermal mismatch between TGO and YSZ, as well as temperature gradient induced thermal stress) are the main degradation reasons for TBCs especially when the topcoat is below 250 μm [14]. Moreover, it has been stated that the formation and evolution of TGO at the interface of TBC/BC is usually seen as the most crucial region for the spallation of TBCs when the top coat is below 250 μm, thus the evolution of the residual stresses in TGO have significant effects on the degradation of thermal barrier coatings system.

Recent studies [15,16] have demonstrated that the initial formed oxide can be spinel when the bond coat is produced by high velocity oxygen fuel (HVOF) process. Most of the thermally grown oxides adjacent to bond coat is pure alumina, but CSN mixed oxides (Cr_2O_3, spinel and NiO)that can potentially form microcracks can be found at the interface of TBC/TGO. In contrast, according to Ref. [17], a specific thermal shock evaluation was performed after vacuum heat treatment. A dense, uniform and continuous α-Al_2O_3 as a protective oxide can be found in TGO due to the extended stage of steady-state growth of TGO. But it cannot be found the transformation from alumina to CSN mixed oxide after 1428 thermal shock cycles.

The degradation of TBCs produced by atmospheric plasma spraying results from the residual stress in TGO, which have considerably adverse effects on the life-span of TBCs. In our work, a topcoat and a bond coat were deposited by atmospheric plasma spraying onto the heat-resisting iron and nickel-based substrates. It should be noted again that the operation state of land-based gas turbine for power plant is thermal exposure ageing for hundreds of thousands of hours, rather than the running state of gas turbine aero-engine-thermal shock. The TGO growth rate, the distribution of residual stress in TGO, the Quantity of the Spinel Cap Presence at the convex of undulated TGO, as well as the θ-Al_2O_3 to α-Al_2O_3 phase transformation with thermal exposure ageing were systematically investigated.

Table 2
Chemical composition (wt.%) of iron-based alloy RTSi-5.5 substrate.

C	Si	Mn	P	S	Cr	Fe
2.2–3.0	5.0–6.0	<1.0	<0.2	<0.12	0.5–0.9	Bal.

2. Experimental details

2.1. Materials and thermal spraying process details

The heat-resisting iron RTSi-5.5 (R-) and nickel-based superalloy Inconel-718 (I-) (Chemical compositions are listed in Table 1 and Table 2) disks (Ø25.4 mm × 3 mm) were used as the substrates, and a grit blasting machine was employed to eliminate the surface oxides and significantly improve the bond coat adhesion (pressure of grit blasting:0.8 MPa, angle:80°–90°, size of sand:150–180 μm corundum sand). And then the substrates were cleaned by a mixture of absolute ethyl alcohol and acetone solution. Deposition of NiCrAlY bond coat (Sulzer Metco, Amdry 962, particle range: −106 to +53 μm, USA) (Chemical composition of Amdry 962 is listed in Table 1) was carried out by an air plasma spraying facility (APS-2000 system, China). The 150 μm bond coat was prepared by thermal spraying parameters as shown in Table 3. Finally, the topcoat was deposited by APS facility (APS-2000 system, China), using 8YSZ (Sulzer Metco 204B-NS,HOSP™,particle range:−75–+45 μm, USA) commercial powder to prepare 500 μm thickness deposition. As shown in Fig. 1a and b, the thicknesses of the as-deposited topcoats onto the R- and I-substrates were approximated to 500 μm, and a number of pores with a wider diameter distribution mainly resulting from the melting powder particles built-up by high plasma energy can be found. Although the cast iron alloys cannot lose their strength of structure if the utilized limitation temperature of cast iron alloys are always ranged from 700 °C to 800 °C, it is very undesirable that the temperature of 700–800 °C for isothermal oxidation can effectively compare the influence of superalloy substrate and cast iron alloy substrate on the thermally grown oxides. As far as the thermodynamics of different chemical compositions of alloys been concerned, 1050 °C is a proper temperature of isothermal oxidation although the structure of the cast iron alloy cannot endure in such relatively high temperature. Consequently, three specimens with both R-substrate and I-substrate set in the high temperature furnace were subjected to 1050 °C isothermal oxidation. The specimens with R-substrates were conducted in a high temperature furnace at 1050 °C for 0.67, 2.5, 15, 50 and 100 h, another ones with I-substrates were carried out at 1050 °C for 0.67, 2.5, 15, 50, 100, 300, 811 and 1199 h, and then cooled to the room temperature. The data of measurement point were taken from the three specimens and then calculated statistically.

2.2. Evaluations of properties of thermal barrier coatings

Specimens sectioned into small portions by diamond saw machine were mounted in epoxy to ensure that the ceramic top coat remained intact. The FE-SEM (S-4800, Hitachi Inc., Japan) – a cold field emission electron microscope equipped with an EDS analyzer (INCA, Oxford Instrument Inc., England) was applied to measure the TGO thickness (15 typical positions each specimen) and analyze the elements of thermally grown oxides after thermal exposure ageing. To characterize and identify the presence of spinel cap at the convex of undulated TGO, the mode of the FE-SEM was consistently set to MIX-BSE & SE mode.

The Cr^{3+} luminescence spectroscopy can be used to measure the residual stress in alumina ceramics. In general, the spectrum of unstressed α-Al_2O_3 shows R_1 and R_2 lines from Cr impurities and the R_2 peak shift of alumina can be analytically investigated as a function of residual stress in TGO if the alumina is subjected to a uniform stress [18–23]. The residual stress in the TGO can be measured at the room temperature using a high-performing Renishaw Ramanscope 2000 (Renishaw™, Gloucestershire, UK) in conjunction with an Olympus BH-2 microscope (50× lens). The laser (He–Ne, 632.8 nm) was focused at the positions along a

Table 3
Parameters of atmospheric plasma spraying regarding bond coat and topcoat respectively.

Parameters	APS(BC)	APS(TC)
Current (A)	550	600
Voltage (V)	60	70
Stand-off distance (in.)	3.9	4.7
Powder feedrate (g/min)	35	35
Primary gas pressure (Ar, psi)	80	80
Secondary gas pressure (H, psi)	36	36
Powder carrier pressure (Ar, psi)	44	44