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Porosity analysis and oxidation behavior of plasma sprayed YSZ and YSZ/$LaPO_4$ abradable thermal barrier coatings

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ABSTRACT

In this research, the high temperature oxidation behavior, porosity, and microstructure of four abradable thermal barrier coatings (ATBCs) consisting of micro- and nanostructured YSZ, YSZ-10%$LaPO_4$, and YSZ-20%$LaPO_4$ coatings produced by atmospheric (APS) method were evaluated. Results show that the volume percentage of porosity in the coatings containing $LaPO_4$ was higher than the monolithic YSZ sample. It was probably due to less thermal conductivity of $LaPO_4$ phases. Furthermore, the results showed that the amount of the remaining porosity in the composite coatings was higher than the monolithic YSZ at 1000 °C for 120 h. After 120 h isothermal oxidation, the thickness of thermally growth oxide (TGO) layer in composite coatings was higher than that of YSZ coating due to higher porosity and sintering resistance of composite coatings. Finally, the isothermal oxidation resistance of conventional YSZ and nanostructured YSZ coating was investigated.

1. Introduction

Gas turbine efficiency can be improved by increasing operating temperatures and gas pressure in the combustion chamber [1–3]. The operating temperature can be increased by applying zirconia based thermal barrier coatings (TBCs) on the hot sections of gas turbine blades [3]. The gas pressure can be adjusted by improving the sealing between the rotating and stationary parts [1].

To this end, abradable seal coatings are applied to the rubbing surface of the stationary part of the gas turbine to reduce the clearance between the coating and the rotating parts [4,5]. Abradable seal coatings act as a sacrificial layer and minimize the operating tip clearance by allowing the blades cutting through them while keeping wear in the blade tip to a minimum [2,5]. Thus, the abradable seal coatings should be soft enough to prevent damage to the tip blade when the rotating blade tip rubs against the stationary casing (good abradability) [5,6]. On the other hand, the abradable seal should be hard enough to withstand erosion by the high-speed gas flow and solid particles in the hot gas (good erosion resistance) [6]. Furthermore, the high temperature abradable seal coatings operating in the hot section of gas turbine must also have other required properties such as high melting point, phase stability, oxidation and corrosion resistance, and high expansion coefficient [1,3]. Yttria-Stabilized Zirconia (YSZ) is the most common ceramic used as a high temperature abradable coating that satisfies most of the required properties [7,8]. Furthermore, considering the low thermal conductivity of YSZ powder, it can act as a TBC in addition to being an abradable coating prevents the damages resulting from the heat transfer to the substrate [3,6]. The abradable thermal barrier system similar to conventional thermal barrier system consists of several different layers including: the YSZ top coat, metallic bond coat, and superalloy substrate [1,9]. The metallic bond coat increases the oxidation resistance of the substrate at high temperatures and also increases the adhesion of the coating to the substrate [9].

By exposing the coating to high temperatures, the thermal grown oxide (TGO) layer also forms at the interface of the bond coat/top coat. The TGO is a very thin layer (1–10 μm) mostly consisting of Al_2O_3 and a little of Cr_2O_3, NiO, and Ni (Al, Cr)$_2$O$_4$ spinel [10]. Although, the TGO formation improves the oxidation resistance and further increase in the thickness of this layer increases the internal stresses and reduces the lifetime of the coating [5,11].

However, the basic problem with the YSZ ATBCs is the very high hardness of YSZ bringing about degradation of top of the blade when it strikes [1,2]. The studies show that porosity plays a basic role in the abradable behavior of the ATBCs. By increasing the porosity value, the coating hardness decreases and its abradable behavior improves [2,12]. Therefore, researchers such as Bardi

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et al. [1] and Sporer et al. [2] have improved the abradability behavior by increasing the amount of porosity in YSZ abradable coatings. In order to further improve the abradability behavior of these coatings, a high temperature solid lubricant can also be added to the YSZ coating [2]. Yet, materials such as h-BN [2], Ti_3SiC_2 [13], and $LaPO_4$ [3,13,14] have been added to YSZ coating as the high temperature solid lubricants.

Among these lubricants, $LaPO_4$ powder has been of high interest due to its high melting point, low thermal conductivity, phase stability, and high expansion coefficient [14,15]. In a research performed on YSZ/$LaPO_4$ composite, Ren et al. [3] reported a reduction in thermal conductivity by an increase in the amount of $LaPO_4$. Additionally, they have reported that by the addition of more than 20 wt% of $LaPO_4$ to YSZ, the cubic phase of YSZ will be stabilized with unfavorable properties. Zhao et al. [13] have also studied the effect of the addition of $LaPO_4$ and Ti_3SiC_2 powders as two different solid lubricants on YSZ TBCs. According to their report, only the $LaPO_4$ lubricant can keep its phase stability at high temperatures. Furthermore, they observed that by an increase in the amount of $LaPO_4$, the Young's modulus of coating was also decreased. They have also reported a reduction in the hardness value by an increase in the amount of $LaPO_4$ powder. In a research work performed on YSZ/$LaPO_4$ composite, Min et al. [16] reported that $LaPO_4$ showed no affinity to react with YSZ at high temperatures and was considered a very suitable lubricant in this regard. However, there is little information in the literature regarding the porosity analysis and the oxidation resistance of YSZ/$LaPO_4$ coating at high temperatures. By exposing the ATBCs to high temperatures and sintering the coating, their amount of porosity is reduced [17,18]. By decreasing the amount of porosity, therefore, their abradability behavior is reduced over time [2,5]. Additionally, by a reduction in the amount of porosity, the thermal conductivity of the coating also increases and therefore, its thermal barrier behavior is weakened [17,18]. For this reason, in this study, the microstructural changes of YSZ/$LaPO_4$ and conventional YSZ coating (porosity content) at high temperature was investigated. Finally, the oxidation resistance of micro-YSZ was compared to nanostructured YSZ TBCs.

2. Experimental procedure

2.1. Material preparation

The Inconel 718 alloy with a dimension of 10 × 10 × 5 mm was used as the substrate in this research. The YSZ powder (ZrO_2-8% Y_2O_3-2008P-PAC-USA) was used as the main part of the top coat and the NiCrAlY (Cr 22%-Al 10%-Y 1%-Ni bas- 60.46.8-GTV- Germany) as the bond coat. Lanthanum phosphate was also prepared by the reaction between phosphoric acid (85%- Fulica) and lanthanum oxide (≥99.5%- 112,220- Merck- Germany). The XRD pattern of lanthanum oxide is shown in Fig. 1a. The lanthanum oxide was calcined for two hours at 700 °C to remove the absorbed water. To produce lanthanum phosphate, the calcined lanthanum oxide was first slowly added to diluted phosphoric acid with a mole ratio of 1–2 and stirred for 30 min to fully accomplish the reaction between phosphoric acid and lanthanum oxide. After the termination of the above reaction, the product was washed with deionized water for several times to completely remove the remaining phosphoric acid. Then, the product was exposed to 100 °C for 24 h. Later, the $LaPO_4$ powder was calcined for four hours at 900 °C to remove the remaining water in its structure. Moreover, the irreversible transformation of hexagonal to monoclinic could also take place [19]. Then, the product was crushed and suitable powders were sieved for thermal spraying process (40–120 μm). The XRD pattern of product (lanthanum phosphate) is depicted in Fig. 1-b. Ultimately, the $LaPO_4$ powders with two ratios of 10 and 20 wt% were added to YSZ powder and mixed for 4 h to obtain a homogenous composition.

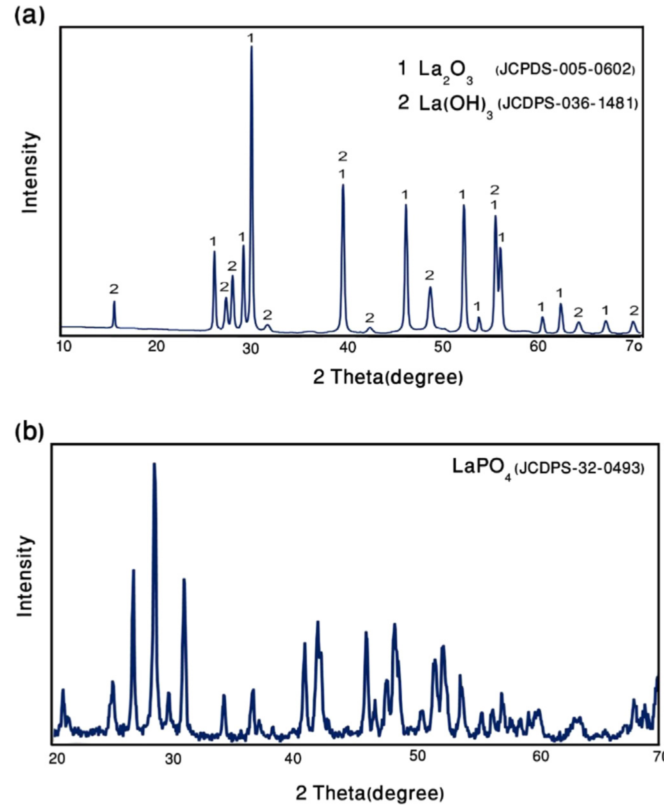

Fig. 1. XRD patterns of (a) La_2O_3 and (b) $LaPO_4$ after 900 °C calcination.

2.2. Preparation of plasma sprayed coating

After sand blasting of the substrate, by the use of SiC abrasive particles with a mesh size of 25, a bond coat of NiCrAlY with a thickness of 120–170 μm was applied on the substrate surface by the use of APS process. Then, three coatings of YSZ, YSZ-10 wt% $LaPO_4$, and YSZ- 20 wt% $LaPO_4$ with a thickness of 600–800 μm were applied on the bond coat surface by the use of APS method.

The ceramic powders of nanogranules of 7YSZ (consisting of agglomerated nanosized particles 15–100 μm in diameter) were produced by the sol-gel and spray drying method, respectively. The APS parameters for nano- and micro-YSZ powders are presented in Table 1. The APS parameters for the top coat were specified on the basis of the design of an experiment method (DOE) to produce a significant amount of porosity in the microstructure.

2.3. Oxidation test

The isothermal oxidation test was performed at 1000 °C for 30, 60, and 120 h inside an electric furnace with air atmosphere. In

Table 1
Parameters of plasma spraying.

Parameter	Bond coat	Micro-YSZ, Top coat	Nano-YSZ
Current (A)	600	500	600
Secondary gas, H_2 (l/min)	6	4	10
Primary gas, Ar (l/min)	35	35	35
Powder feed (g/min)	40	25	18
Spray distance (cm)	15	11	