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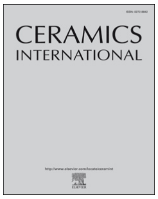

Influence of SiC fiber on thermal cycling lifetime of SiC fibers /YSZ thermal barrier coatings by atmospheric plasma spraying

Yongchao Fang, Xiufang Cui*, Guo Jin*, Bingwen Lu, Fuyuan Wang, Ming Liu, Xin Wen

Institute of Surface/Interface Science and Technology, Key Laboratory of Superlight Material and Surface Technology of Ministry of Education, College of Material Science and Chemical Engineering, Harbin Engineering University, Harbin 150001, China

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ABSTRACT

The initiation and propagation of cracks under thermal stresses easily is one of the problems limiting the thermal cycling lifetime of thermal barrier coatings (TBCs). In order to improve the thermal cycling lifetime, SiC fibers were introduced to yttria stabilized zirconia (YSZ) coating deposited on In738LC substrate by atmospheric plasma spray (APS). Phase composition, thermal cycling behaviors and fiber toughening mechanisms of coatings were systematically investigated by X-ray diffraction (XRD), scanning electron microscopy (SEM) and thermal cycling test. Results showed that the thermal cycling lifetime and fracture toughness of SiC fibers/YSZ coatings could reach 442 ± 13 and 1.54 ± 0.19 MPa $\sqrt{m}$ respectively, which were 1.6 times and 1.3 times higher than that of conventional TBCs. There are two stages of fiber reinforced during thermal cycling, and the first is crack deflection and termination, the second is fiber debonding, pull-out, breakage and bridging. Meanwhile, SiC fibers could prevent the stress-activated ZrO_2 martensitic transformation by reducing the stress in the lattice.

1. Introduction

Thermal barrier coatings (TBCs) have been widely applied to prevent overheating and oxidation of the key components working at elevated temperatures, such as turbine blade, combustion chamber and so on [1–3]. At present, the state-of-the-art TBCs consisted of a bond coat of MCrAlY (M usually consists of Ni, Co, or their mixture [4]) and a top coat of partially yttria-stabilized zirconia (YSZ) ceramic [5]. The YSZ/NiCoCrAlY TBCs have prominent thermal insulation properties and a wide application range. However, thermal cycling lifetime limits the further application of the conventional YSZ coatings because of more stringent service environment for new type of gas turbine [6,7]. It is necessary in order to extend the thermal cycling life of YSZ TBCs as much as possible. As it is known, the initiation and expansion of cracks are one of the main reasons for the thermal cycling failure. And it is correlated significantly with the stability of interlayer structure [8,9]. Thus, the stability of interlayer structure plays an important role in determining the thermal lifetime of coatings. Therefore, improving the interlayer structure stability of the YSZ coatings is one of the fundamental points to the present study.

The fiber-reinforced has been widely used as the structural stability lifting of block ceramics. These years some scholars have introduced this method into the field of ceramic surface protection materials. Ma et al. [10] investigated that SiC fiber/ YSZ composite coatings showed a rise of thermal cycling lifetime. Xiong et al. [11] evaluated that the carbon-fiber-reinforced aluminum composites had an excellent ultimate tensile strength compared with Al matrix. But the SiC fiber and carbon fibers were wrapped on the substrate by using SiC fiber felt and unidirectional carbon fiber bundles before spraying. The ceramic coating was 4 mm-thick multilayer structure which is composed of SiC fiber/ YSZ layer and pure YSZ layer and 2 mm thick composite structure, respectively. Thus, the SiC fiber/ YSZ composite coating and carbon-fiber-reinforced aluminum composites were too thick to be the TBCs. In addition, the mechanism of thermal cycling lifetime for fiber-reinforced thermal sprayed coating is not thorough. Therefore, it is necessary to study on the practical coating preparation method and the SiC fiber reinforced mechanism in-depth.

The objective of the present study is to develop SiC fibers reinforced TBCs in effort to improve the thermal cycling lifetime. The YSZ coatings and the SiC fibers/YSZ coating were prepared on In738LC by APS. Microstructure, thermal cycling lifetime, fracture toughness and fiber reinforcement mechanisms of coatings were investigated.

2. Experimental procedure

2.1. Powders and their mixing

Commercially available NiCoCrAlY (purity: >99.5%, average

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* Corresponding author.
E-mail address: cuixf721@163.com (X. Cui).

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particle size: 38–75 µm, supplied by Changsha TITD metal materials Co., Ltd., China), YSZ powder (purity: > 99.5%, average particle size: 50–100 µm, supplied by United Coatings Technologies Co., Ltd., China) and SiC fiber (purity: N99wt%, diameter < 20 µm, Length/Diameter > 20, supplied by Xvzhou HongWuNANO Materials Tech Co., Ltd., China) were used as the raw powder materials.

Two types of TBC samples, the YSZ and the SiC fiber-reinforced yttria stabilized zirconia (SiC fiber/YSZ) coatings, were deposited using the APS system with the bond coat of NiCoCrAlY. The YSZ powders were made of 8 wt% Y_2O_3–ZrO_2 (8YSZ) and the SiC fiber/YSZ powders were comprised of 8 wt% SiC fibers and 92 wt% 8YSZ powders. All the powders were grinded using wet grinding method by a planetary ball mill stirring with the following operating parameters: ball to power to absolute ethyl alcohol weight ratio of 1:1:1, and rotational speed of 300 r/min.

2.2. Coating preparations and air plasma spraying

Inconel 738 (IN-738LC) super alloy with size of *Φ*20 mm × 8 mm (supplied by Shanghai RongKun metal products Co., Ltd., China) was used as the substrate. The substrates were mechanically polished to remove oxide and oil layers on the surface. Then it cleaned by alcohol in ultrasonic for 30 min to remove the oil and impurities. Finally, the substrates were then degreased and grit blasted with brown corundum in order to increase the bonding strength.

Two types of TBCs were deposited by APS (Beijing Aerospace Zhenbang Precision Mechanism., Ltd., China) with F4-type spray gun. The plasma spraying parameters are shown in Table 1. And the total thickness of coating is about 400 µm. The thickness of the bond coat and top coat is about 100 µm and 300 µm, respectively.

2.3. Characterization and testing

Compositions of TBCs were characterized by X-ray Diffraction (XRD) using Cu Kα radiation (X'Pert Pro MPD, PANalytical B.V. company, Netherlands) with scanning velocity of 2°/min, scanning scope of 10–90°, accelerating current of 150 mA and voltage of 40 kV. Morphology of TBCs was observed by scanning electron microscopy (SEM, FEI Quanta 200, FEI Company, Netherlands) before and after thermal cycle experiment.

The fracture toughness of the coating was measured by an indentation method, at a load of 294.2 N for 10 s using a micro hardness tester (HV30, China) after grinding with 1000# sand paper, which could be used for qualitative comparison of samples produced by similar procedure [12]. Fracture toughness (K_{IC}) can be calculated using the following equation after calculating the crack length and other parameters [10]:

$$K_{IC} = 0.016(E/H_V)^{1/2}(P/C^{3/2}) \tag{1}$$

where K_{IC} is the fracture toughness, P is the indenter load, E is the Young's modulus, H is the Vickers hardness, and C is the crack length.

Thermal cycling test as shown in Fig. 1 was conducted by the water quenching method which was reference to the Japan industry standard (JIS8666-1990) and the China industry standard (GB/T 30873-2014) [13]. For every thermal cycle, the coated samples undergo the following steps: (1) the specimens were in a muffle furnace at 1000 ± 10 °C with 5 min dwelling time. (2) The specimens quenched to room temperature via water (25 ± 5 °C) in 1 min (3) Repeated the process for next cycle. When the damage area reached to approximately 20%, the tests were terminated and the thermal cycles are recorded as failure threshold. At the same time, the thermal cycling specimens were photographed with a camera, the changes of the coating surface after each thermal cycle were recorded, and the surface area of the coating was observed and calculated.

Table 1
The plasma spraying parameters.

Parameter	Bond coat	Top coat
Gun nozzle inner diameter (mm)	6	6
Powder injection port inlet diameter (mm)	2	2
Current (A)	550	650
Voltage (V)	65	75
Primary gas Ar (slpm)	55	43
Second gas H_2 (slpm)	2	7
Carrier argon gas flow rate (slpm)a	45	45
Gun traverse speed (mm s1)	100	100
Powder feed rate (g min1)	28	22
Spray distance (mm)	110	110

3. Results and discussion

Pores structure and defects play an important role in interface stability. Coating porosity determined by converting the cross-sectional SEM image of the coating to be binary, using Image-Pro-plus and calculation ratio of black pixels to total pixels. Binary image of double coatings shown in Fig. 2 and calculated porosity for YSZ and SiC fiber/YSZ coating is 12.55% and 12.35%, respectively. There is no significant difference in porosity between the coatings. But more cracks are in YSZ coatings compared with SiC fiber /YSZ coatings, which may be the source of coating failure.

3.1. Fracture toughness and thermal cycling life of coatings

As shown in Fig. 3, the average fracture toughness of YSZ coatings is 1.12 MPa $\sqrt{m}$ and that of SiC fiber/YSZ coatings is 1.54 MPa $\sqrt{m}$, calculated by the Eq. (1). The fracture toughness of SiC fiber/YSZ coatings is much greater than that of the YSZ coatings. In other words, the SiC fiber/YSZ coatings have greater crack-propagation resistance compared to the YSZ coatings [10,14].

To ensure the accuracy of thermal cycling lifetime, more than five samples of each coating are employed to determine the thermal cycling property conducted at 1000 °C. The thermal cycling lifetime of YSZ and SiC fiber/YSZ coatings are shown in Fig. 3. The thermal cycling lifetime of YSZ coatings is 262, while that of SiC fiber/YSZ coatings is 442. It indicates that thermal cycling property of SiC fiber/YSZ coatings is better than that of YSZ coatings.

Fig. 4 displays the photographs and spallation area of YSZ coatings and SiC fiber/YSZ coatings in thermal cycling test. There is no obvious spallation in the first 150 cycles of all coatings, except for small flakes on the edge. However, when the thermal cycling test proceeded to the 175 thermal cycling (C175), the YSZ coating is in large area peeling for the first time. And the YSZ coating is spalling at a stable and high rate, which is larger than that of the SiC fiber/YSZ coatings. When the YSZ coatings are failure (spallation area of 21.22%) with cycles of 262, the SiC fiber/YSZ coatings are less destroyed (spallation area of 13.22%). In addition, the failure of the SiC fiber/YSZ coatings undergoes several stages. In the first one hundred cycles, the thermal cycling resistance of SiC fiber/YSZ coatings is similar to that of YSZ coatings. As the thermal cycling test proceed from C100 to C225, the SiC fiber/YSZ coatings peel off with small debris. And during the next 75 cycles, the SiC fiber/YSZ coatings begin to peel off seriously. But when the SiC fiber/YSZ coatings are in the C300 to C400, they keep the low spallation rate which is almost 0.04% cycles per 10 cycles. After that, the thermal shock test is terminated with thermal cycles of 442 and spallation area of the coatings reaches to 20.44%. Both of coatings failure begins at the edge of the coatings and propagates inwards. And the SiC fiber/YSZ coatings failure area is more concentrated compared with that of YSZ coatings. As we can see, the failure mode of the YSZ coatings is chipping and spalling with large debris, and the failure mode of the SiC fiber/YSZ coatings is spalling with small debris. Therefore, it could be considered that the thermal cycling properties of SiC fiber/YSZ coating are better than that of YSZ coatings.