

Contents lists available at ScienceDirect

Surface & Coatings Technology



Failure analysis of fine-lamellar structured YSZ based thermal barrier coatings with submicro/nano-grains



Y. Wang ^a, Y. Bai ^{a,*}, T. Yuan ^b, H.Y. Chen ^a, Y.X. Kang ^a, W.J. Shi ^a, X.L. Song ^a, B.Q. Li ^c

^a State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an 710049, PR China

^b Beijing Jinlunkuntian Special Machine Co., Ltd., Beijing 100083, PR China

^c Department of Mechanical Engineering, University of Michigan, Dearborn, MI 48128, USA

ARTICLE INFO

Article history: Received 3 November 2016 Revised 20 March 2017 Accepted in revised form 24 March 2017 Available online 27 March 2017

Keywords: Failure analysis Yttria partially stabilized zirconia Thermal barrier coatings Grain size Phase stability

ABSTRACT

The catastrophic phase transformation of yttria partially stabilized zirconia (YSZ) is considered to be the main reason that leads to the failure of YSZ based thermal barrier coatings (TBCs) when their service temperatures are higher than 1200 °C, which greatly limits the application of YSZ in the new-generation aero engines. In the present work, a fine-lamellar structured YSZ coating that consisted of submicro-/nano-grains showed good phase stability during a burner-rig test at 1270 \pm 20 °C. The results from X-ray diffraction and Raman spectros-copy confirmed that the phase compositions of as-sprayed or failed coatings fully consisted of the *t*' phase. The catastrophic tetragonal-monoclinic ($t \rightarrow m$) phase transformation did not occur, indicating it was not the main reason for the spallation of YSZ coating. However, the analysis of residual stress within YSZ coating suggested that the failure of coating was associated with the severe sintering of YSZ and thermal expansion mismatch at high temperatures.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Thermal barrier coatings (TBCs) have been used for many years to protect the hot section components of aero engines against hightemperature environment [1–3]. The most commonly used ceramic material for TBCs is 6-8 wt% yttria partially stabilized zirconia (YSZ) [4–5]. However, YSZ is not considered to be suitable for the long-term operation above 1200 °C [6-7]. When the operation temperature increased (>1200 °C), the Y^{3+} ions within YSZ could diffuse to their equilibrium positions and the metastable tetragonal phase (t') in the plasma-sprayed coating slowly evolved into a mixture of t', yttriapoor tetragonal (*t*) and yttria-rich cubic phase (*c*). Subsequently, the tetragonal-monoclinic (t-m) phase transformation accompanied by a volume expansion of 3–5% and resulted in the premature failure of YSZ coating [8]. Interestingly, some researchers found that the content of *m* phase in the as-sprayed coating did not increase in a burnerrig test, in which the heating temperature reached 1250 °C [9]. The work from Moon et al. also showed that the $t \rightarrow m$ phase transformation was greatly suppressed at a rapid cooling rate [10]. The above results indicated that the YSZ coating was stable when operating at a higher temperature and the potential of this material was needed to be further explored. In addition, the impurity phase in the original YSZ powders (e.g. silicon, aluminum and sodium) easily resulted in the impurities segregation at grain boundaries of coating at elevated temperatures. Meanwhile, the higher content impurities would accelerate the sintering of YSZ and lead to the failure of TBCs [11–13].

The supersonic-plasma-sprayed YSZ (SAPS-YSZ) coating, which consisted of many fine lamellar structures (splats), showed a higher thermal shock resistance than its conventional-plasma-sprayed counterpart at 1100 °C [14]. The fine-lamellar structures could reduce the coating defects and improve the cohesion and adhesion of YSZ coating. Because the in-flight particles melted and broke up through strong coupling with the supersonic plasma jet in thermal and momentum transfer, the deposited particles were significantly smaller in size, resulting in the formation of disk-shaped splats with lower thickness and surface roughness [15]. Nevertheless, the nature of fine-lamellar structures in the grain aspects was still not fully understood. Its evolution with respect to the fine-lamellar structures and phase composition at higher temperatures (~1250 °C) were needed to be further investigated. In addition, the failure driven by the thermal/residual stress in the YSZ coating and developed during cooling after high-temperature treatment, through a sequence of cracks nucleation, propagation and coalescence process [16]. Therefore, in the present work, the phase stability and residual stresses of fine-lamellar structured SAPS-YSZ coating were studied in order to provide an insight into the failure reason of YSZ based TBCs.

2. Experimental methods

The substrate, one nickel-base superalloy (GH4169) with dimension of $Ø30 \text{ mm} \times 6 \text{ mm}$, was ultrasonically cleaned and then grit-blasted

^{*} Corresponding author. *E-mail address:* byxjtu@mail.xjtu.edu.cn (Y. Bai).

Table 1

Spraying parameters for CoNiCrAIY and YSZ powders.

	-	
Parameters	CoNiCrAlY	YSZ
Power (kW)	49.8	68.6
Current (A)	380	497
Voltage (V)	131	138
Primary gas Ar (slpm)	75	70.5
Secondary gas H ₂ (slpm)	8	22
Spray distance D (mm)	110	110
Feed rate (g min ^{-1})	35	35

with alumina powder in order to increase the adherence capability between bond coat and substrate. A commercially available CoNiCrAlY powder (AMDRY 995 M, Sulzer Metco Inc., USA) with nominal composition of Ni-32, Cr-21, Al-8, Y-0.4 Co-balance (wt%) with average particles size about 65 μ m was used to fabricate the bond coat. The spraydried and sintered ZrO₂-8 wt% Y₂O₃ (YSZ) powders (SY-133, Sang Yao Technical Co., Ltd., China) with a particle size of 10–45 μ m were used for depositing the top coat. The small particles inside the feedstock were well compacted with sizes of 150–580 nm. Both the bond coat and the top coat were deposited by high-efficiency supersonic atmospheric plasma spraying (SAPS) system. The spray parameters are listed in Table 1.

The phase compositions of the samples were characterized by X-ray diffraction (XRD, D/MAX-2400X, Rigaku, Japan) using Cu Kα radiation $(\lambda = 0.15406 \text{ nm})$ at 40 kV and 40 mA. The range of scattering angle (2θ) was from 10° to 90° with a scan step of 0.008°. The in-plane residual stress (parallel to the interface) within the top coat was measured by X-ray diffraction (the $\sin^2 \varphi$ method) for as-sprayed and thermal cycled coatings. Raman spectroscopy (HR800, Horiba, France) was also employed to analyze the phase compositions due to its particular sensitivity to the presence of monoclinic zirconia. The microstructure of samples was observed by scanning electron microscopy (SEM, VEGAII XMU, Tescan, Czech Republic) and high resolution transmission electron microscopy (HRTEM, JEM-2100F, JEOL, Japan). In order to further reveal the grain boundaries, phases, and other microstructural details, the specimens were etched. The thermal etching was conducted at 1250 °C for 3 h in a furnace, and then cooled down to the room temperature. Some microstructural informations of as-sprayed or failed coatings, such as grain size distribution, porosity and crack content etc., were obtained by a quantitative image analysis method (IA) using Image-Pro Plus software (Media Cybernetics, Silver Springs, MD). The final statistical result was the average value from ten cross-sectional micrographs of the individual specimen.

In order to determine the fracture toughness of coatings, Vickers indentations were performed on polish cross-sections using a hardness tester. The indentation load was 5 N. Both Vickers diagonals and crack lengths were measured by SEM. The fracture toughness of as-sprayed coating was calculated by the following equation [14]:

$$K_c = 0.203 (c/a)^{-3/2} H V_p a^{1/2}$$
⁽¹⁾

where HV_p is the Vickers hardness, *a* is the half of the average length of two indents diagonal and *c* is the half of average crack length. Besides, the bonding strength of the as-sprayed coating was measured by the tensile test in accordance with ASTM C 633-79 standard. The film epoxy adhesive (FM-1000, USA) with tensile fracture strength >60 MPa was applied. The final value represented the average of 3 samples sprayed at the same parameters.

Thermal shock resistance of samples was evaluated by a burner-rig test. The surface morphology of the samples was observed by a CCD camera. During thermal shock test, the surface temperature was heated to 1270 ± 20 °C (~50 s) using the combustion flame of propane-oxygen gas mixture and the backside of samples was cooled by compressed air with a flow rate of 40 mL·min⁻¹, then holding for 5 min at this temperature. After holding stage, the samples were rapidly cooled down to room temperature (~30 s). The spalled region >10% on the surface of the top coating was adopted as the criteria for the failure of the samples.

Thermal insulation test was carried out by a self-made set-up in our previous experiments [17]. Thermocouple 1 was used to measure the front side temperature inside the electrical furnace (*T*1). Thermocouple 2 was used to measure the temperature of the back side of a reference sample outside the electrical furnace (*T*2). The reference sample was defined as one with only metallic bond coat and without YSZ top coat. Thermocouple 3 was used to measure the temperature of the back side of as-sprayed/thermal cycled samples outside the electrical furnace (*T*3). Thereby, the thermal insulation temperature ($\Delta T = T2 - T3$) was directly used to evaluate the thermal insulation property of TBCs, and the higher the ΔT was, the better the thermal insulation property was.

3. Results

3.1. Microstructure of as-sprayed coating

Fig. 1 shows the TEM images of as-sprayed YSZ coating. As seen from Fig. 1a, many polyhedron-shaped grains with an average size of 250 nm were observed after the fusion and recrystallization of the original feedstock powder. The selected area electron diffraction (SAED) patterns



Fig. 1. TEM images of (a) submicron grains and (b) nanograins in the as-sprayed coating.

Download English Version:

https://daneshyari.com/en/article/5465373

Download Persian Version:

https://daneshyari.com/article/5465373

Daneshyari.com