Wear 271 (2011) 2909–2918

Contents lists available at ScienceDirect

Wear

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

Solid particle erosion of thermal spray and physical vapour deposition thermal barrier coatings

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ARTICLE INFO

Article history:
Received 21 December 2010
Received in revised form 27 May 2011
Accepted 9 June 2011
Available online 16 June 2011

Keywords:
Solid particle erosion
Thermal spray coatings
High temperature
Electron microscopy

ABSTRACT

Thermal barrier coatings (TBC) are used to protect hot path components of gas turbines from hot combustion gases. For a number of decades, in the case of aero engines TBCs are usually deposited by electron beam physical vapour deposition (EB-PVD). EB-PVD coatings have a columnar microstructure that guarantees high strain compliance and better solid particle erosion than PS TBCs. The main drawback of EB-PVD coating is the deposition cost that is higher than that of air plasma sprayed (APS) TBC. The major scientific and technical objective of the UE project TOPPCOAT was the development of improved TBC systems using advanced bonding concepts in combination with additional protective functional coatings. The first specific objective was to use these developments to provide a significant improvement to state-of-the-art APS coatings and hence provide a cost-effective alternative to EB-PVD. In this perspective one standard porous APS, two segmented APS, one EB-PVD and one PS-PVD™ were tested at 700 °C in a solid particle erosion jet tester, with EB-PVD and standard porous APS being the two reference systems.

Tests were performed at impingement angles of 30° and 90°, representative for particle impingement on trailing and leading edges of gas turbine blades and vanes, respectively. Microquartz was chosen as the erodent being one of the main constituents of sand and fly volcanic ashes. After the end of the tests, the TBC microstructure was investigated using electron microscopy to characterise the failure mechanisms taking place in the TBC.

It was found that PS-PVD™ and highly segmented TBCs showed erosion rates comparable or better than EB-PVD samples.

1. Introduction

Ceramic thermal barrier coatings (TBCs) are widely applied for protecting hot path components of gas turbines from combustion gases. By using this refractory ceramic porous layer deposited on surfaces of base materials of vanes, blades, transition pieces and combustion chambers, the temperature on metallic substrates can be reduced by 30–150 °C depending on the thickness and on the specific properties of the coating [1]. The state-of the-art of these TBCs is represented by yttria (partially) stabilized zirconia (YPSZ) (7–8 wt.% $Y_2O_3 + ZrO_2$) deposited onto the components either by air plasma spray (APS) or by electron beam physical vapour deposition (EB-PVD) [1].

Owing to the deposition process, APS TBC show a porous microstructure consisting of a superposition of ceramic lamellar shaped splats, interlamellar fine penny shaped pores and either trans granular or intergranular microcracking with the major axis oriented perpendicular and parallel to the TBC surface, respectively. On the other hand, EB-PVD coatings have mostly columnar microstructure (even the porosity among columns shows a columnar structure) that guarantees higher strain compliance but lower thermal insulation compared to APS TBC [2–5].

To improve strain compliance and erosion resistance of APS TBC, keeping the deposition costs lower than EB-PVD coatings, dense vertically cracked APS TBC have been developed within the last decades. These coatings consist of a quite dense microstructure segmented by vertical cracks penetrating most of the TBC thick-

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doi:10.1016/j.wear.2011.06.013

ness. Depending on the crack density, the strain compliance of these coatings can be significantly improved. At the same time the dense microstructure guarantees a better resistance to solid particle erosion. A thermal conductivity comparable with EB-PVD coating is the main drawback of these coatings compared to standard APS TBC [6].

In aero gas turbines, blades & vanes and combustors & transitions are usually coated by EB-PVD and APS TBC, respectively. On the contrary, for land based applications hot path components of most of the engines are coated by APS TBC.

Main failure mechanism of TBCs during service (or testing at high temperatures) is governed by the thermally grown oxide (TGO) at the interface between the metallic bondcoat and the ceramic coating and by the mismatch of thermal expansion coefficients between the ceramic layer and the metallic substrate. Depending on the operating (or testing) conditions one of these two phenomena can be predominant compared to the other one. In any case, both these effects are the driving forces for nucleation, propagation and coalescence of cracks parallel to the interface between ceramic top coat and the metallic bondcoat up to the TBC spallation [7–13].

Solid particle erosion is another failure mode of TBC. This is especially true for aero gas turbines operating in sandy (or ashy) environments, but even for land based gas turbines, where air is filtered before entering the compressor stage, solid particle erosion can take place owing to particles escaped from filters, or produced either within compressor stages or in the combustion chamber, depending on the materials and on the operating conditions of the specific engine. Owing to their inertia, solid particles do not move along the flow streamlines and thus they impact on components eroding the protective coatings from the base materials. Pressure loss, change in blade geometry and overheating of base metals are the main effects of erosion in gas turbines [14–16].

Erosion mechanisms in APS and EB-PVD coatings differ significantly because of their different microstructure, as described in the next section.

In this work, the main results of high temperature solid particle erosion tests on three innovative and on two reference TBCs systems are reported. The effect of impingement angle and speed on erosion rates has been investigated. The different failure modes for the five tested systems have been studied by scanning electron microscopy.

2. Review of erosion mechanisms in TBCs

2.1. APS coatings

Following the work of Eaton and Novak, three different types of solid particle erosion can be distinguished in APS TBCs [14]:

- primary scars as principal observable feature on the erosion surface (low erosion rate),
- occurrence of fractures around the impact area on the coating surface (moderate erosion rate),
- tunnel formation on the surface (high erosion rate).

In the first case impacting particles produce mainly indentations on the surface and erosion takes place as material loss caused by successive impacts on deformed material. In the second type of mechanism impact produces crack propagation along splat boundaries. In the third case the kinetic energy transferred from the particles to the target is high enough to connect pre-existing pores inside the TBC eroding clusters of several splats each time.

They also found a correlation between the strength of TBC as measured by four point bending test and the erosion rate (the higher the first the lower the second). When the overall porosity is fixed, the erosion rate increases as a function of the specific surface area of the porosity. Starting from these results they proposed a linear relationship between the erosion rate w_e and the ratio of the normalised specific area C (i.e. the area per unit of weight and of volumetric porosity content) to the strength σ:

$$w_e = a\frac{C}{\sigma} + b \tag{1}$$

where a and b are constants. As also predicted by models for bulk ceramics, erosion rate is strongly dependent on the ratio of the coating to particle micro-hardness, independently from the porosity fraction, as shown by Janos et al. [17]. When the particle microhardness is fixed, the dependence is just on the coating microhardness.

Nichols et al. and Li et al. describe the erosion of APS TBC as occurring through spalling off surface lamella resulting from impact of erodent particles [18,19]. Accordingly, the erosion of the coating is controlled by crack propagation along the interface between neighbour lamellae. In other words, APS fails by propagation of cracks around splat boundaries and through the microcrack network. This means that the higher the percentage and/or the strength of the bonded interface among lamellae the lower the erosion rate. Starting from the McPherson modelling of a plasma sprayed coatings [20], Li et al. describe the erosion rate as proportional to the lamellar interface bonding ratio α, the lamellar thickness δ and the effective surface energy of lamellar material γ_c [19]:

$$w_e \propto \frac{\rho_c E_{eff}}{2\gamma_c \alpha} x \tag{2}$$

where ρ_c and E_{eff} are the density of the target and the fraction of the kinetic energy per unit mass of impacting particles promoting cracking, respectively. Here $2\gamma_c\alpha$ is the fracture toughness of the TBC. They also report that if a weaker bonding between lamellae of two different passes is observed a higher erosion rate occurs [19].

Since sintering process promotes the bonding between lamellae, an increase of the erosion resistance of APS TBC is reported in the literature for aged samples [19,21].

2.2. EB-PVD coatings

In the case of EB-PVD coatings the columnar structure is responsible for damage modes not comparable with those typical of bulk ceramic materials and APS coatings. In particular, Wellman and Nicholls and Chen et al. describe three possible modes [21–25].

2.2.1. Mode I (near surface cracking/lateral cracking)

When small particles impact on EB-PVD TBC surface with a sufficiently low speed, the top 20 μm of the individual columns are cracked due to impact. Following Chen, in this experimental condition the response of the TBC is only elastic and cracking parallel to the surface are caused by tensile stresses promoted by the elastic waves propagating forward and backward along each single columns all around the impingement site. Reduced erosion rates correspond to this damage mode. This damage mode has been observed both at RT and at high temperature even if at high temperature the erosion rates differ because of the temperature dependence of elastic modulus hardness and fracture toughness of TBC.

A limited amount of cracks occur even deeper than 20 μm. This type of cracks usually is initiated at the base of the dendritic column edge structure [21–24].

2.2.2. Mode II (compaction damage)

Due to impingement of particles with slightly higher momentum (speed and or mass) compared to the previous case, a