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Numerical simulation of segmentation cracking in thermal barrier coatings by means of cohesive zone elements

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Abstract

The paper presents comparative experimental and numerical studies of segmentation cracking of thermal barrier coatings (TBCs) during three point bending tests. The finite element simulation of failure development was performed using a cohesive zone approach. Acoustic emission (AE) technique and in situ observations by a charge-coupled device (CCD) camera allowed to determine critical strain values correlated with the damage evolution. Location of crack initiation and crack propagation paths up to macroscopic failure were investigated for as-received and annealed specimens. The results of the numerical simulations and of the experiment were quantitatively similar. The influence of critical energy release rate on crack patterns was examined, resulting in the increase of crack numbers due to decreased value of G_{I}. This explains the good spallation resistance of electron beam-physical vapour deposition (EB-PVD) coatings, where G_{I} is lower than in the case of air plasma sprayed (APS) thermal barrier coatings. Lower value of G_{I} stimulates segmentation cracking and reduces delamination, as observed within electron beam-physical vapour deposition coatings.

Keywords: Cohesive zone modelling; Segmentation cracking; Thin film coating; Bending test

1. Introduction

The improvements in increasing the efficiency of gas turbines within the past 20 years have been partially achieved by applying thermal barrier coatings (TBCs) on components such as turbine blades of the first and second rows, where the high temperature loading is dominant. However, the mechanisms leading to failure and the parameters limiting coating lifetime have not been fully revealed so far. Therefore, the full potential of thermal barrier coatings as an important factor allowing for further increase in the gas turbine inlet temperature is still not fulfilled.

Under normal operation conditions coated turbine blades experience rather complex loading, combined with the existence of residual stresses and oxidation processes. Therefore, it is difficult to predict the dominant driving force to cause the failure. Additionally, the microstructure of the constituents, namely TBC, bond coat (BC) and the substrate, continuously changes and modifies the mechanical response. Only lab-scale testing offers the opportunity to define ideal loading profiles. In this context, simple bending tests offer ideal conditions to study crack initiation and damage evolution under purely mechanical loading. Additionally, tests performed before and after high temperature annealing and with variation of loading rate allow to cover a wider range of failure-influencing parameters. Especially oxidation processes at the BC/TBC interface are expected to significantly modify the damage evolution.

Different testing techniques with the goal of studying the influence of mechanical strains on damage evolution and failure have been reported in the literature. Schmidt et al. [1] performed creep tests under constant tensile stress on specimens coated with an air plasma sprayed (APS) thermal barrier coating. The TBC adapted to the deformation by forming cracks perpendicular to the surface. These cracks started mainly at the BC/TBC interface and grew up to the free surface. The probability of segmentation cracking increased with increasing creep rate, TBC thickness and amount of pores between the sprayed layers. Döpper et al. [2] performed strain controlled tensile tests on specimens with APS and electron beam-physical vapour deposition (EB-PVD) coatings. The EB-PVD coatings resisted a strain of 25%, without showing any delamination. Only a dense

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network of cracks perpendicular to the tensile direction could be observed. The APS coating split into segments at the strain around 3%, but no delamination was observed during subsequent stretching, cf. Zhou et al. [3]. During four point bending tests with the APS-TBC under tensile loading, it was observed that segmentation cracks formed usually with a constant spacing equal to the doubled value of TBC thickness, see Andritschky et al. [4]. Due to increased loading, the cracks deflected at the BC/TBC interface leading to delamination of the protective layer, see Zhou et al. [3]. Four point bending tests with the coating under compression revealed delamination cracks at the BC/TBC interface at lower strain values after pre-oxidation when compared to the non-oxidised specimens, see Moriya et al. [5].

Problematic in all the investigations is the precise detection of a critical strain value at which the TBC starts to undergo a process of damage localisation and formation of macroscopic cracks. Indeed, long before the appearance of visible cracks, the TBC undergoes a phase of macroscopically homogenous quasi-plastic deformation, occurring mainly due to the growth of microcracks and frictional gliding. These processes are known to be accompanied by acoustic emission (AE) phenomena, see Ma et al. [6]. Monitoring of AE signals should therefore lead to a more precise determination of critical strain values.

The concept of a cohesive zone ahead of a crack tip, stemming from works by Barenblatt [7] and Dugdale [8], has been extensively used to simulate crack nucleation and propagation in composites and brittle materials. Mróz and Białas [9] and Białas and Mróz [10] formulated a cohesive zone model using the formalism of the theory of plasticity. They analysed instability points associated with quasi-static progressive and cyclic delamination processes. Camacho and Ortiz [11] used a cohesive fracture model to simulate propagation of cracks along arbitrary paths. Surface-like cohesive elements were introduced at the interfaces between standard volume elements. Crack branching and coalescence could be naturally handled by this approach. Simulation of dynamic crack propagation have been presented in the papers by Pandolfi et al. [12] and Zhou and Molinari [13,14] in three dimensional problems. Tijssens et al. [15] used the damaging cohesive surfaces to study concrete fracture.

Rangaraj and Kokini [16,17] analysed the influence of segmentation cracks on stress distribution and fracture resistance of functionally graded thermal barrier coatings. The cracks were a priori introduced into a finite element mesh and assumed to remain stationary during temperature loading. Kokini and Takeuchi [18] examined the effect of multiple cracking within graded TBC on the value of critical energy release rate for an interface crack between the coating and the substrate. They found that multiple segmentation cracks can reduce the magnitude of critical energy release rate for the interface and thus, be beneficial for the life of the coating. Rangaraj and Kokini [19] used a two dimensional finite element model with a cohesive zone to study quasi-static crack growth due to a heating–cooling cycle. Xie and Tong [20] incorporated a cohesive interface model into two dimensional analysis of cracking and delamination of thin Al_2O_3-film on a ductile substrate. Caliez et al. [21] used a debonding model based on the work of Tvergaard [22] to simulate spallation of EB PVD coatings.

The current paper presents results of three point bending tests performed with the TBC subjected to tensile in-plane stresses. Acoustic emission and simultaneous optical inspection of the interface area were used as in situ diagnostics. This allowed to examine the correlation between continuously increasing strain and the process of macroscopic crack formation and propagation. The critical strain values leading to crack initiation were thus identified. Crack growth and configuration were further investigated together with the influence of deformation rate and the pre-oxidation process. The results of APS TBC segmentation cracking during three point bending test were further compared to numerical simulations of the experiment. Time dependent effects within the bond coat and TBC layers were not accounted for. It was assumed that both the beam substrate, being CMSX-4 super-alloy, and the bond coat layer were elastic–plastic materials, whereas TBC proved to be elastic. The irreversible processes within the coatings were captured by means of cohesive zones serving as potential regions for TBC cracking. To capture the segmentation cracking of the coating, they were placed between the solid elements of the coating and allowed a crack to propagate from the free surface and to remain arrested at the TBC/BC interface. A constitutive model for failure evolution, proposed by Mróz and Białas [9] and Białas and Mróz [10], was used. The influence of critical energy release rate of TBC material on crack patterns was further examined.

2. Three and four point bending tests

2.1. Experimental set-up

Standardised three point bending tests (EN 843-1) at room temperature were performed on TBC coated samples before and after annealing for 300 h at 1050 °C. The Ni-base single crystal alloy samples (CMSX-4) had a length of 50 mm, a width of 3.5 mm and an average thickness of 2.5 mm. On the top surface an MCrAlY-type bond coat was applied by vacuum plasma spraying with an average thickness of 150 μm. Two different methods, air plasma spraying and electron beam-physical vapour deposition were used for producing 250 μm (EB-PVD) and 300 μm (APS) thick TBC. The TBC consisted of a partially stabilised (6–8 wt% Y_2O_3) Zirconia. The TBC/BC interface roughness was in the order of $R_a = 6–7$ μm (technical measure). Prior to applying the EB-PVD coating, the BC surface had been smoothed and the interface roughness did not exceed the value of $R_a = 1$ μm.

The tests were performed on a universal testing facility (Instron, type 1362). Displacement of the points laying on samples symmetry axis were measured inductively using a scanning stick. They were further used to calculate the strain ϵ at the TBC/BC interface by using formula

$$\epsilon = \frac{3}{8}\frac{(h_{sub} + h_{BC})w}{L^2}. \quad (1)$$

$h_{sub} + h_{BC}$ is the sum of substrate and bond coat thicknesses, w is the measured displacement and L the distance between two