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Letter

A new spallation mechanism of thermal barrier coatings on aero-engine turbine blades

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HIGHLIGHTS

- EB-PVD TBCs can spall off at room temperature under constant residual stresses.
- The mechanism of blister growth relies on pockets of energy concentration (PECs).
- The nucleation and stable growth of the blister are driven by PECs.
- The unstable growth and spallation of the blister are driven by PECs and buckling.

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ABSTRACT

Laboratory experiments were conducted to study the spallation behaviour of thermal barrier coatings (TBCs) on aero-engine turbine blades manufactured by the electron-beam physical vapour deposition technique (EB-PVD). Intact blades were heated at temperature 1135°C in a furnace for certain time and then cooled to the room temperature in the laboratory condition. It was found that no spallation occurred during cooling, but spallation happened at constant room temperature after cooling. The spallation mechanism is studied by using the mechanical model developed (Harvey 2017 and Wang 2017), which are based on the hypothesis of pockets of energy concentration (PECs). Some observations of the spallation behaviour are well predicted by the model.

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Thermal barrier coatings (TBCs) can protect the engine components from high and prolonged heat loads, improve the durability and the engine energy efficiency [1, 2]. In the layered TBC system, an yttria-stablized zirconia (YSZ) ceramic top coat is bonded on the metallic substrate by either an overlay or a diffusion bond coat. During thermal exposure, a layer of thermally grown oxide (TGO) is generated at the interface between the top coat and the bond coat.

TBCs can degrade and spall off from the alloy substrate at elevated temperatures or room temperature, then the exposed substrate will be oxidized and melted [3, 4]. The mechanisms of this spontaneous spallation failure are very complex and have stimulated considerable research studies with various considerations including sintering [5], oxidation [6], interface adhesion degradation [7], thermal stress due to the mismatch in coefficient of thermal expansion between the coating and the substrate [8], creep [9], and interface undulation geometry [4]. In the previous experiments, such as indentation test [10, 11], bending and buckling test [12, 13], scratch test [14] and push-out test [15], coupon samples were out of the blade shape; for the samples that cut from the blade, minor flaws could appear during preparation. The stress and strain fields in coupon samples may then be different from those in the intact blades. Therefore, the entire blades were tested in the present study. Specially, the top coat was coated by the electron-beam physical vapour deposition technique, and bonded by a γ/γ' Pt-diffused bond coat which

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exhibits negligible rumpling due to the high creep resistance in heating-cooling cycles [16].

Extensive analytical and numerical studies have been carried out in last few decades for the spallation behaviour of TBC. Most studies are based on buckling driven delamination [4, 6, 10-13, 17-19]. However, the buckling driven approach is insufficient to reveal the essential mechanics as discussed in the work [20, 21]. Wang, Harvey et al. [22, 23] recently developed a mechanical model, which hypothesized that pockets of energy concentration (PECs) resulted from pockets of interfaces stresses, and would be the driving energy for constant room temperature spallation failure. The aim of the current study is to apply the mechanical model in the work [22, 23] to study the spallation of TBCs, and compare the analytical predictions with experimental measurements.

It is believed that an introduction to the mechanical model by Wang, Harvey et al. [22, 23] is helpful to understand the present work.

Figure 1 sketches a circular separation blister of TBC with radius R_B and thickness h. The subscript B represents the edge of the blister.

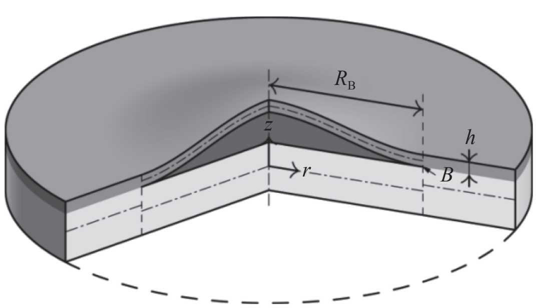

Fig. 1. A circular separation blister of TBC.

The blister grows when the driving force at the crack tip, i.e., energy release rate (ERR) overcomes the fracture toughness. Different fracture partition theories lead to different mode mixity [24, 25]. The following derivations are based on the classical plate partition theory [24, 26, 27]. Using the linear fracture criterion, the blister energy at growth is

$$(U_a)_{GR} = \pi R_B^2 G_c \left\{ \frac{3}{2} + \frac{6\bar{\varepsilon}_0}{\pi^2} \left(\frac{R_B}{h}\right)^2 \left[\frac{3}{\pi^2 \phi_0} \left(\frac{R_B}{h}\right)^2 - 1 \right] \right\}, \quad (1)$$

where $\bar{\varepsilon}_0 = \sigma_0 \left(1 - \nu^2\right)/E = \sigma_0/\bar{E}$ is the residual plane strain with σ_0 representing the biaxial compressive residual stress, and $\phi_0 = h\sigma_0/G_c$. E and ν are the Young's modulus and Poisson's ratio of the TBC material, and G_c is the fracture toughness at the interface between the TGO and the bond coat. For the nucleation of the blister, the higher order terms of R_B can be neglected. Then the Eq. (1) suggests that the PECs need to provide the blister energy $(U_a)_{NU} = 3\pi R_B^2 G_c/2$ and NU denotes the blister nucleation.

After nucleation, the blister grows slowly until the radius reaches the characteristic buckling length. Then, unstable growth starts at

$$\left(\frac{R_B}{h}\right)^2_{UG} = \frac{\pi^2 \phi_0}{12} \left[1 - \left(1 - \frac{\alpha^2}{\Omega}\right)^{1/2} \right], \quad (2)$$

where UG denotes the unstable growth, and $\Omega = \bar{\varepsilon}_0 \phi_0/2 = h{\sigma_0}^2/\left(2\bar{E} G_c\right)$ is the ratio between the residual plane strain energy density and the interfacial fracture toughness. The parameter α is introduced to consider the effect of amplitude A, which can be considered an initial imperfection. In the work [22, 23], α is considered an effect of boundary conditions. Its range is therefore $0.652 \le \alpha \le 1.220$ with the two limits corresponding to simply-supported and clamped edge conditions respectively. The interface fracture toughness G_c decreases with the service time increasing for TBCs, leading to a larger Ω. Therefore, the value of Ω is generally much larger than α^2, i.e., $\Omega >> \alpha^2$. Then, Eq. (2) becomes

$$\left(\frac{R_B}{h}\right)^2_{UG} = \frac{(\alpha\pi)^2}{12\bar{\varepsilon}_0}. \quad (3)$$

It is worth noting that the mentioned characteristic buckling is different from the bifurcation type buckling. In the conventional approach for buckling-driven delamination, the amplitude A of the blister is zero at the instant of the buckling. However, the amplitude A of the blister hereby is with a finite value. Hence, it is expected that the non-bifurcation type buckling occurs well before the bifurcation type buckling.

The violent unstable growth rapidly enlarges the size of the blister, and the blister energy will increase to a maximum value as suggested by Eq. (1). If the PECs are insufficient to supply the blister to arrive the maximum value, then the blister will stop growing. After the maximum value, the blister energy will decrease and transform into the kinetic energy. If the blister energy becomes zero and the kinetic energy of the blister due to the fast-unstable growth is large enough to break the blister edges, then the blister will spall off from the substrate. The spallation radius is calculated as

$$\left(\frac{R_B}{h}\right)^2_{SP} = \frac{\pi^2 \phi_0}{6} \left[1 - \left(1 - \frac{3}{2\Omega}\right)^{1/2} \right], \quad (4)$$

with SP denoting spallation. From Eq. (4), it is seen that Ω has to be larger than 3/2 for spallation to occur. When $\Omega >> 3/2$, Eq. (6) becomes

$$\left(\frac{R_B}{h}\right)^2_{SP} = \frac{\pi^2}{4\bar{\varepsilon}_0}. \quad (5)$$

The blister amplitude A is given in Eq. (6) below.

$$\left(\frac{A}{h}\right)^2 = \frac{96\bar{\varepsilon}_0}{\pi^4 \phi_0} \left(\frac{R_B}{h}\right)^4. \quad (6)$$

It is worth noting that only the blister radius R_B was measured whilst the amplitude A (out-of-plane displacement) was not measured in the present work since only one digital camera was used in the experiment.

The above derivations can be equally applied for either classical plate partition theory [24, 26, 27] or first-order shear-deformable plate partition theory [26, 27] or 2D elasticity plate partition theory [25, 28, 29]. However, the interface fracture toughness G_c needs to be taken as $G_c = G_{Ic}$, $G_c = 4\psi G_{Ic}/\left(3 + \psi\right)$ and $G_c = \psi G_{Ic}/\left(0.3773 + 0.6227\psi\right)$ respectively for the three partition theories, where G_{Ic} is the critical mode I fracture toughness

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