The influence of creep properties on crack propagation in thermal barrier coatings

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Abstract. Thermal barrier coatings are used to protect turbine blades from the high temperature of the process gas inside a turbine. They consist of a metallic bond coat and of a ceramic top coat with low thermal conductivity. During service, an additional oxide layer forms between bond coat and top coat that eventually causes failure. Finite element simulations show that the roughness of the interface between top and bond coat is crucial for determining the stress state. Lifetime models have been inferred that assume that cracks form in the peak positions at small oxide thickness and propagate when the oxide layer grows and the stress field shifts. A two-dimensional finite element model of crack propagation in the TBC layer is presented. Since the cracks propagate near a material interface and since plasticity may occur in the bond coat, standard tools of fracture mechanics for predicting the crack propagation direction are difficult to apply. This problem is circumvented in a very simple way by propagating short “test cracks” in different directions and optimising to find the crack direction with the maximum energy release rate. It is shown that the energy release rate and the crack propagation direction are sensitive to the details of the stress state and especially to the creep properties of the materials. Implications for failure models are discussed.

1. Introduction
Modern turbine blades are coated with thermal barrier coatings to partially protect the base material from the hot gas. The full potential of these coatings is difficult to exploit because they fail after some time by spallation for reasons that are not completely understood [1]. A thermal barrier coating system comprises a metallic bond coat that serves as corrosion protection, a ceramic top coat (the TBC in the narrower sense), and an oxygen layer that forms at the interface during service (TGO, thermally grown oxide). Usually, coatings spall upon cooling when this oxide layer reaches a critical thickness of the order of 10 µm [2, 3].

There are two causes of stress in the coating system: The difference of the coefficient of thermal expansion between the coating materials causes thermal stresses. Furthermore, the growing oxide layer has a larger volume than the bond coat it forms from, leading to growth stresses. It has been suggested [4] that cracks form initially at the peaks of an interface asperity because the stress is tensile here for a thin TGO. When the TGO grows, the stress state at the peak region becomes compressive, and the region of tensile stress shifts to the valley position. It has been assumed that cracks would follow the tensile region. However, this model takes not into account that a forming and growing crack would change the stress field. In this paper, a model of a thermal barrier coating system is presented that includes crack propagation. Creep
2. Finite element model

The model geometry (see Fig. 1) is that of a solid cylindrical disk which is thought to be infinitely extended in its axial direction, almost identical to the model described in [5]. The geometry was meshing using approximately 15000 four-node elements with selectively reduced integration and was implemented using the standard finite element program ABAQUS. Material data can be found in table 1. Growth of the TGO was implemented by using the swelling-option in ABAQUS. Isotropic swelling with a constant growth rate during each cycle was assumed.

To thermally load the system, the system temperature is isothermally raised from 20°C to 1000°C within 60 s. It is held at hot temperature for 120 s or 1 200 s, and cooled back in another 60 s to 20°C.

After performing one thermal cycle, a crack of size 0.375 µm is initiated at the peak position of the TBC at the position of highest stress, directly above the TGO. This initial crack serves as starting point for the subsequent crack propagation calculation. Because the stress state is multi-axial and the crack is close to an interface, it is difficult to apply standard tools of fracture mechanics to predict the crack propagation direction. Therefore, we use a simple, but CPU-intensive, technique in which trial cracks are propagated in different directions, performing one finite element simulation per trial crack [7, 8]. The energy release rate during crack propagation is measured in each simulation by calculating the change in the energy stored in the system. It is assumed that the direction with the highest release rate is the direction in which the crack
Figure 2. Crack propagation as a function of the creep strength of TGO and TBC (in MPa s\(^{-1}\)). Left: Total accumulated crack length (in µm) before the energy release rate becomes smaller the initial energy release rate. If the creep strength is low, cracks propagate throughout the simulation volume. Right: Initial value of the energy release rate in J/m\(^2\). Note the change in perspective relative to Figure 2(a)

would propagate. If this is larger than the critical energy release rate \(G_c\), the crack propagates in this direction and another crack increment is calculated. If it is smaller than \(G_c\), the crack does not propagate and the state of the system is reset to the configuration before the crack increment. Throughout this paper, the trial crack length is fixed at 0.75 µm.

3. Results
To check the standard failure model described in the introduction, crack propagation simulations with a thin TGO layer were performed. After one thermal cycle with hold time 120 s, a crack was introduced at the peak position near the TGO/top coat interface. If the failure model is valid, a crack should be able to propagate and then stop. To study this, the simulation was run with a critical energy release rate \(G_c\) of zero so that the crack would propagate unhindered until it has crossed the full simulation volume. The energy release rate was measured throughout to see whether the energy release rate becomes lower than the initial energy release rate (which is the condition for a stopping crack). The creep properties of top coat and TGO were varied.

Figure 2 shows the results results of the variation of the creep pre-factors. Figure 2(a) shows the crack length for which the energy release rate drops below its initial value. This is thus the minimum crack length before a crack might stop. In materials will low creep strength, the crack cannot stop because the energy release rate never becomes smaller than the initial value, whereas a high creep strength leads to a decrease of the energy release rate with increasing crack length. Figure 2(b) shows the absolute value of the initial energy release rate. Although cracks in creep-soft materials would not stop once they have started, the absolute value of the energy release rate is rather small so that crack propagation would probably not begin.

These results show that the standard failure model can only be valid if the creep strength of the coating materials is sufficiently large. Furthermore, reducing the creep strength might be beneficial for the lifetime of the coatings because the energy release rate for crack propagation becomes smaller.

In the simulations shown above, the absolute values of the energy release rate after one thermal cycle shown in the previous section were small. In this section, the energy release rate
of the first crack increment is measured after each of several thermal cycles (with hold time 1 200 s per cycle) to see whether it increases to more realistic values when the TGO grows. To do this, the critical energy release rate $G_c$ was set to a very high value so that the crack could not propagate. Due to the TGO growth, the radial stresses at the peak position of the TBC become compressive with increasing number of cycles. This is shown in Figure 3(a). Nevertheless, as Figure 3(b) shows, the energy release rate increases despite the increase in compressive stresses. Thus, crack propagation occurs in mode II in this model. The results indicate the simple assumption of a failure model as sketched in the introduction may be wrong. However, crack propagation in mode II would require a larger energy release rate because friction between the crack surfaces would dissipate energy that is not available for creating new surface. In the future, the model will be improved by adding a friction coefficient on the crack surfaces.

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