Modeling crack spreading in thermal barrier coatings

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Introduction

Thermal barrier coatings (TBCs) are nowadays widely applied in gas turbines and airplane engines to allow higher operating temperatures and thus higher efficiencies. The porous ceramic top coating (typically yttria stabilized zirconia, YSZ) in conjunction with active cooling of the base material leads to the formation of a thermal gradient between hot gas and turbine component. Consequently, the gas temperature can be raised without reaching critical temperatures in the component base material.
However, the TBC may fail (i.e. crack or spall) during operation as a result of several degradation mechanisms, such as, micro-crack growth induced by thermal and/or mechanical loading or chemical degradation. Currently there is a considerable deficit in the knowledge of the evolution of crack initiation and crack growth up to macroscopic delamination. Therefore it is necessary to develop a deeper understanding of the damage evolution under isothermal, thermo-cyclic, but also thermo-mechanical loading conditions.
The aim of this work is to develop a TBC lifetime model for currently used atmospheric plasma sprayed (APS) thermal barrier coating systems based on the mechanical strain necessary to cause failure of the coating.

Experimental

System investigated:

Substrate	Bond coat	Top Coat
CMSX-4	**150 µm VPS NiCoCrAlY**	**300 µm APS Yttria Stabilized Zirconia (YSZ)**

Oxidation parameters:

- Isothermal oxidation at 1000 °C for 1000 h to establish pre-damage
- Thermo-mechanical gradient fatigue (TGMF) testing at 930°C with
  - 0.3% mechanical strain in-phase (8min hot dwell)
  - 0.3% mechanical strain out-of-phase (8min hot dwell)

Results — Critical Strain Measurement

The two-step damaging mechanism that is observed on APS TBCs is shown in figure 1 [1,2]. The first step is micro-crack-growth in the ceramic top coating (mixed mode cracking) which leads to a macroscopic delamination crack parallel to the YSZ-bond coat interface (fig. 1a). This is followed by macroscopic through cracking of the ceramic as shown in figure 1b.

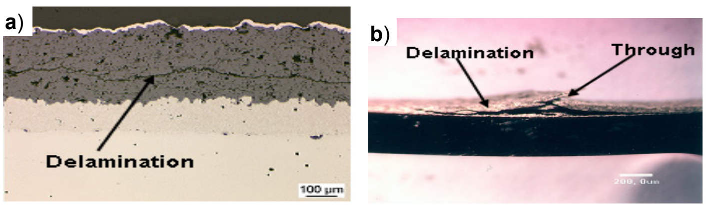

Figure 1:
Optical images of TBC failure after 4-point bend testing. The two-step failure process leads to delamination parallel to the interface at first (a), followed by through cracking of the TBC (b) [1,2].

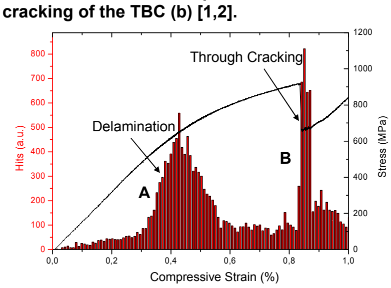

Figure 2:
Typical data set acquired during 4-point bending experiment (conducted in compression). The acoustic emission signals are shown in red, the stress strain curve in black.

The critical strain that leads to delamination or through cracking of the TBC can be measured for example in mechanical 4-point bending experiments with in-situ acoustic emission monitoring. A typical result of a 4-point bending experiment with acoustic emission measurement is shown in figure 2. The stress-strain curve is plotted as black line, the acoustic emission signals are plotted in red. The first increase in acoustic emission can be attributed to step 1 in the damaging process - micro-crack growth in the YSZ top coat and the evolution of a delamination crack parallel to the interface. The second peak in the acoustic emission signal coincides with the steep drop in the stress-strain curve and corresponds to the second step - through-scale cracking and complete failure of the coating. Additional critical strain measurement was carried out by compression testing of hollow cylindrical samples.

Project Partners

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Results — Modeling Isothermal Exposure

The presented lifetime model uses a fracture mechanics approach derived from the Griffith theory [3,4] and attempts to model the critical strain, which is necessary to cause TBC damage. Four equations can be derived from the classical theory that describe the different failure modes:

	Tension	Compression
Delamination	$\varepsilon_{cr}^{d+} = \frac{2K_{IIc}}{f \; E_{Ox}\sqrt{\pi c}}$ (1)	$\varepsilon_{cr}^{d-} = -\frac{K_{Ic}}{f \; \sqrt{\pi c}} \; \frac{(1+r/d)\;(1+\nu)}{2E_{Ox}}$ (2)
Through cracking	$\varepsilon_{cr}^{s} = \frac{K_{Ic}}{f \; E_{Ox}\sqrt{\pi c}}$ (3)	$\varepsilon_{cr}^{sh} = -\frac{2K_{IIc}}{f \; E_{Ox}\sqrt{\pi c}}$ (4)

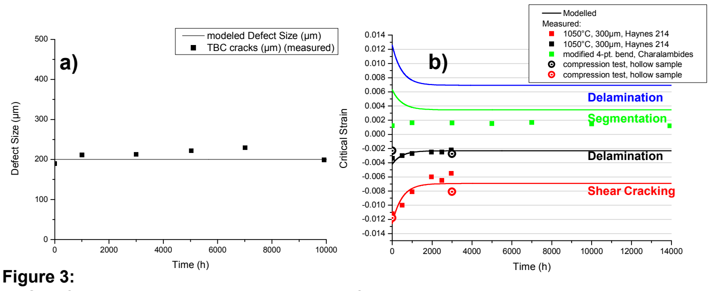

Figure 3:
TBC defect size evolution as determined from metallographic cross sections (a) and calculated critical strain values for the different failure modes in comparison with measurement data (b).

The defect size is a high-impact parameter in equations (1)-(4), therefore it was determined experimentally from metallographic cross sections. No significant increase during isothermal exposure up to 10000h was observed (fig. 3a). The resulting critical strains are in acceptable agreement with the measurement data, only the measurement data derived from the Charalambides test yields lower values than predicted. However, this could be due to the fact that this test is carried out in tension and crack growth just prior to the observed separation might have occurred.

Results — Modeling Cyclic Exposure

The application of the model to cyclic (TGMF) exposures is shown in figure 4. The measured defect size shows a linear increase after ~1300 cycles, which results in a kink in the critical strain curves at this position. Measured critical strain values show reasonable agreement for shear cracking and good agreement for delamination (both in compression). No experimental data is available in tension so far.

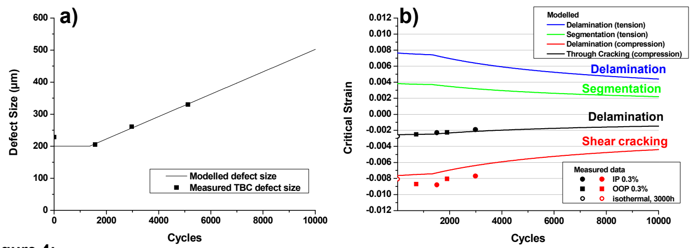

Figure 4:
TBC defect size evolution with thermo-mechanical loading (a) and calculated critical strain values for the different failure modes in comparison with measurement data (b). The approach for lifetime assessment is sketched in (c).

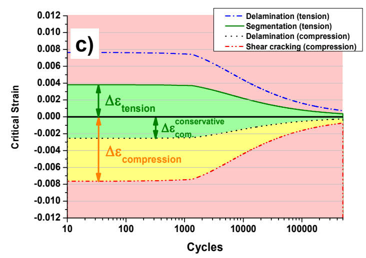

Figure 4c describes the approach of assessing lifetimes from the modeled critical strain values. To completely avoid damage in a component the strain levels occurring in one cycle have to remain within the green area. That is, both, the tensile strains and the compressive strains have to be lower than the border-lines of the green area (conservative) or yellow area (less conservative, interfacial delamination is tolerated). For a given strain level present during one cycle, the lifetime of the component can be assessed by finding the intersection point with a border-line and reading the value for the cycles from the abscissa.

References

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