Development of a mechanism-based lifetime model for bi-layer thermal barrier coating systems

M. Rudolphi, M.C. Galetz, M. Schütze
e-mail: rudolphi@dechema.de

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Introduction

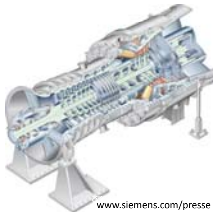
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Fig. 1: Schematic of a modern gas turbine.

Thermal barrier coating (TBC) systems are a state-of-the art materials solution for the hot section of industrial gas turbines, where a ceramic coating in combination with internal air cooling is used to generate a thermal gradient across the ceramic. This allows higher gas temperatures whilst maintaining a tolerable metal temperature. Nevertheless, a continuing demand for increased efficiency and lower CO_2 emission is pushing the operating temperatures into a range beyond the phase stability limits of yttria stabilized zirconia (YSZ). Bi-layered thermal barrier coatings consisting of a gadolinium zirconate (GZO) layer on top of a layer of standard YSZ ceramic are a proposed solution to reach even higher operating temperatures. However, reliable production routes and the mechanical stability of such coatings with reasonable lifetime have to be ascertained before the industrial use is feasible. Thus, establishing a robust production route and development of a lifetime model for bi-layer TBCs are in the focus of this project.


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Fig. 2: TBC coated blades and vanes inside gas turbine.

Bi-Layer Thermal Barrier Coatings

The investigated system consists of a nickel based PWA1483 substrate, coated with a CoNiCrAlY LCO22 bond coating. The two ceramic layers were a bottom-layer of 8wt.% yttria stabilized zirconia (YSZ) and a top-layer of gadolinium zirconate ($Gd_2Zr_2O_7$, GZO) prepared by atmospheric plasma spraying. This layering of two different ceramic materials combines the increased phase stability of GZO with the good adherence and high toughness of YSZ ceramics. However, the lower fracture toughness of GZO requires profound knowledge of mechanical damage mechanisms and the critical loading conditions at which failure will occur.

The bi-layer system shows significantly improved lifetime in the cyclic burner rig test with a surface temperature of 1400°C. The results show that a stoichiometric GZO layer and a tailored microstructure (esp. porosity) are essential to assure superior coating performance.

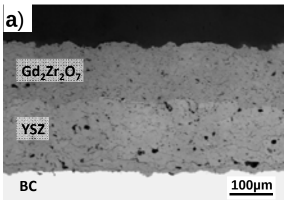


Fig: 3: Bi-Layer TBC system produced at FZ Jülich.

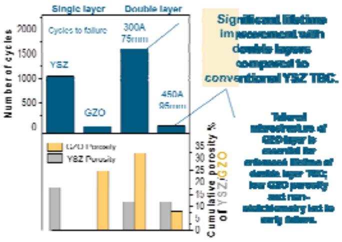
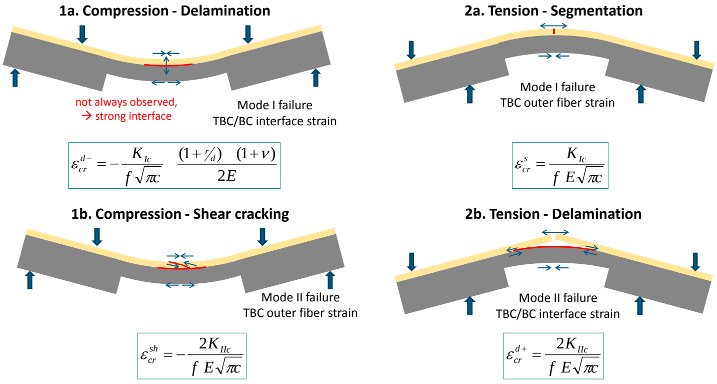


Fig: 4: Cyclic lifetime of single-layer and bi-layer TBC coatings (burner rig test, FZ Jülich) and porosity levels.

Theoretical Background

The lifetime model is based on a fracture mechanics approach derived from the Griffith theory [1,2] and models the critical strain, at which TBC damage will occur. Four equations can be derived from the classical theory that describes different failure modes [3]. These four failure modes can occur in both ceramic layers (GZO and YSZ) and are investigated in experimental 4-point bending experiments.



$$\varepsilon_{cr}^{d-} = -\frac{K_{Ic}}{f\sqrt{\pi c}}\,\frac{(1+{}^{r}\!/_{d})\quad(1+\nu)}{2E}$$

$$\varepsilon_{cr}^{s} = \frac{K_{Ic}}{f\;E\sqrt{\pi c}}$$

$$\varepsilon_{cr}^{sh} = -\frac{2K_{IIc}}{f\;E\sqrt{\pi c}}$$

$$\varepsilon_{cr}^{d+} = \frac{2K_{IIc}}{f\;E\sqrt{\pi c}}$$

with: ε_c – critical strain; K_{Ic} – fracture toughness; E – Young's modulus; c – physical defect size; r – interface roughness; d – coating thickness; ν – Poisson's ratio; f – geometry factor

Fig: 7: Failure modes in pure bending and corresponding modeling equations.

4-Point Bend Testing

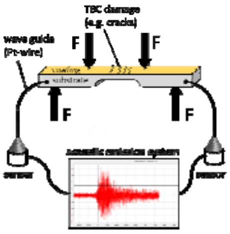
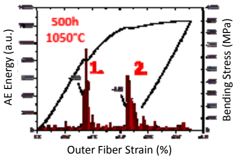
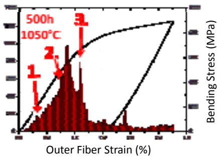


Fig: 5: Schematic of the 4-pt. bend setup with AE sensors.

Mechanical stability of the novel bi-layer coatings is investigated by 4-point bend testing with in-situ acoustic emission (AE) measurement. The use of two AE sensors allows to locate the origin of the acoustic signal and thereby elimination of background noise. The coatings are tested in both, tensile and compressive loading conditions.

Typical results obtained from the bi-layer coatings show two distinct peaks in compressive loading conditions, which correspond to shear failure of (1) the GZO top layer and (2) shear failure of the underlying YSZ layer. Tensile bend testing leads to a relatively broad peak that is the combined signal of (1) segmentation failure of the GZO, (2) delamination at the GZO/YSZ interface and finally (3) segmentation of the YSZ-layer.





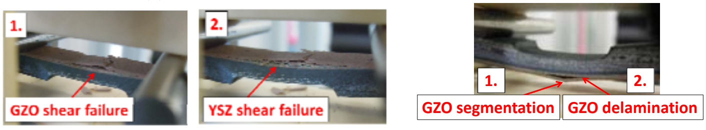
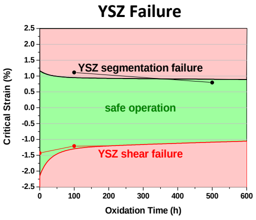
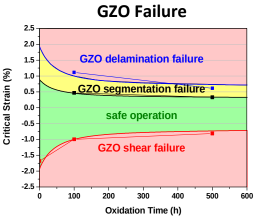


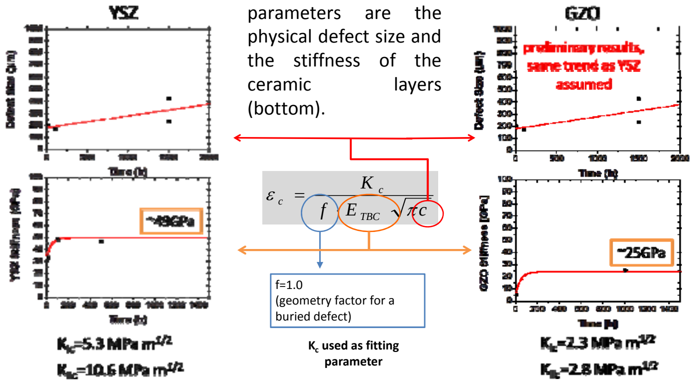
Fig: 6: Typical AE signal in compressive setup (left) and tensile setup (right) and macrographs of the specimen

Lifetime Modelling



The mechanical stability diagrams (top) for each of the two ceramic layers delineate areas of safe operation (green) from areas where failure of ceramic layer becomes imminent. The most dominant damage parameters are the physical defect size and the stiffness of the ceramic layers (bottom).





$$\varepsilon_c = \frac{K_c}{f\;E_{TBC}\sqrt{\pi c}}$$

f=1.0
(geometry factor for a buried defect)

K_c used as fitting parameter

K_{Ic}=5.3 MPa m$^{1/2}$
K_{IIc}=10.6 MPa m$^{1/2}$

K_{Ic}=2.3 MPa m$^{1/2}$
K_{IIc}=2.8 MPa m$^{1/2}$

Project Partners

TECHNISCHE UNIVERSITÄT DARMSTADT
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M. Frommherz,
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R. Vaßen

References

[1] Griffith, A.A., Philos. Trans. R. Soc. London, Series A, Vol. 221 (1921), 163-198.
[2] Dieter, G.E.: "Mechanical Metallurgy", McGraw-Hill, Kogakusha Ltd, Tokyo, 1976.
[3] Schütze, M.: "Protective Oxide Scales and Their Breakdown", Wiley, Chichester, 1997