Design Geometry Optimization of Vertical Cracks in Thermal Barrier Coatings From Simulated Thermal and Mechanical Behavior

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Abstract

Thermal Barrier Coatings (TBCs) have long been used in industry for high temperature applications. Inclusion of vertical cracks in TBCs is an active research area (Figure 1) [1-5]. Traditional plasma spray coatings have randomly oriented cracks due to rapid solidification during deposition (Figure 1a) whereas new technologies produce vertically cracked coatings (Figure 1b&c). Due to the unavoidable coefficient of thermal expansion (CTE) mismatch between the coatings and the substrates, interfacial stress arises when the system undergoes temperature change. Vertical cracks provide strain tolerance within the top layer, therefore providing extra mechanical stability. Some control over crack geometries has been demonstrated [3-4]. The purposes of this simulation are to understand how crack geometry affects coating performance and identify optimizable design parameters. Key parameters are crack-to-crack distance, crack width, and crack depth. COMSOL "Thermal Stress" and "Heat Transfer in Porous Media" modules are employed in modeling a two-dimensional system. A 2800 µm SiC base representing a turbine blade section is covered with a 10 µm environmental barrier coating (EBC) of mullite ($3Al_2O_3 \cdot 2SiO_2$), and a 200 µm TBC of yttria-stabilized zirconia (YSZ). Consistent with experimental observations from our group and others [3-4], vertical cracks are placed in the YSZ at varying crack density, width, and depth. A steady working temperature is assigned to the SiC with the blade cooling by external means. External forced convection is applied to represent surrounding combustion gases. Steady-state stress, strain and temperature are evaluated throughout the profile. Stress minimization throughout the TBC/EBC coatings is the primary mechanism to interpret optimized crack characteristics from this model. Preliminary results demonstrate a temperature diagram (Figure 2) through the TBC/EBC/base consistent with published results (Figure 3). The cross-sectional stress profile (Figure 4) shows that stress peaks at the EBC/base interface. It is also evident that the stress slightly decreases within the TBC coating, and dramatically lessens where vertical cracks begin. This significant stress drop demonstrates the mechanical stress relief capability of vertical cracks. Variation of crack spacing from 80 µm to 110 µm showed that interface stresses decrease as crack density increases. Complete results will include dependence of stress, strain, and temperature profiles on an expanded crack density range as well as several homogenous and heterogeneous crack depths and widths. Influence of crack shape such as tip geometry will also be explored. Vertical cracks are reported in TBC/EBC systems and experimentally observed to increase coating tolerance to thermal stress. However, an ideal crack density and depth are not well understood.

Here, COMSOL is utilized to target crack characteristics for minimizing stresses in a TBC/EBC system. Results of this simulation have active industrial relevance.

Reference

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2. Gray, D., Lau, Y., Johnson, C., & Borom, M. (2001). Thermal barrier coatings having an improved columnar microstructure. US Patent 6,306,517.
3. Taylor, T., Appleby, D., & Bolcavage, A. (2012). DENSE VERTICALLY CRACKED THERMAL BARRIER COATINGS. US Patent 20120003102A1.
4. Xie, L., Chen, D., Jordan, E. H., Ozturk, A., Wu, F., Ma, X., Cetegen, B. M., et al. (2006). Formation of vertical cracks in solution-precursor plasma-sprayed thermal barrier coatings. Surface and Coatings Technology, 201(3-4), 1058–1064. doi:10.1016/j.surfcoat.2006.01.020.
5. Padture, N. P., Gell, M., & Jordan, E. H. (2002). Thermal barrier coatings for gas-turbine engine applications. Science (New York, N.Y.), 296(5566), 280-4. doi:10.1126/science.1068609.

Figures used in the abstract

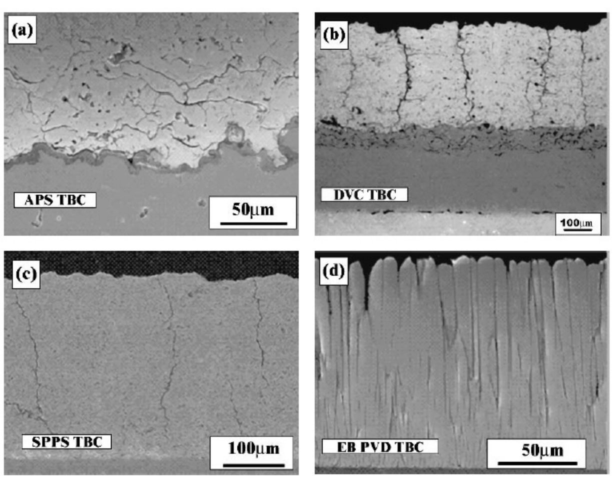

Figure 1: Comparison of (a) traditional plasma sprayed TBC (b&c) TBC with vertical cracks (d) EB-PVD TBC [1].

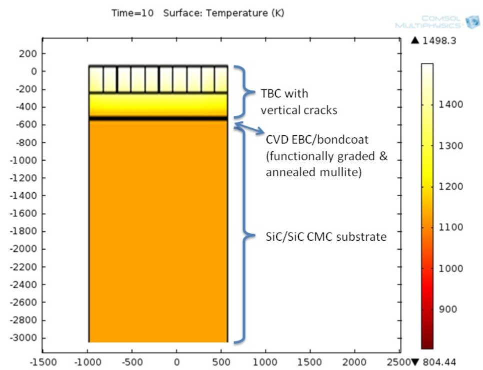

Figure 2: Surface temperature plot of model at steady-state analysis.

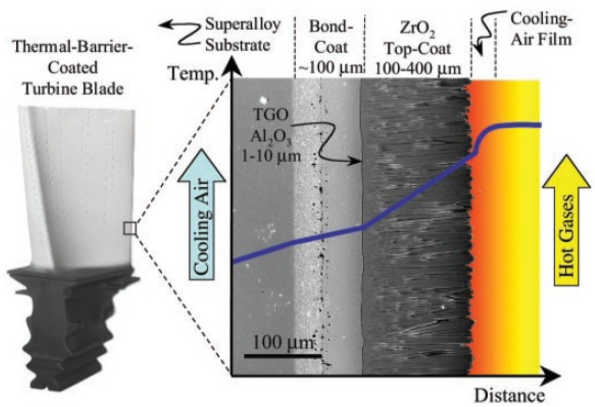

Figure 3: Cross-sectional view of a TBC over turbine blade, the blue diagram shows the temperature reduction by TBC [5].

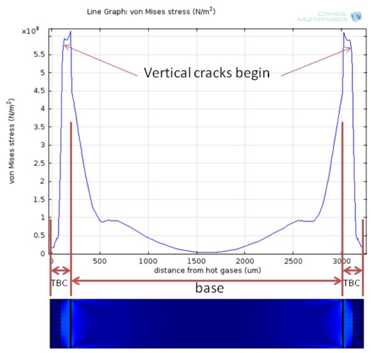

Figure 4: Surface stress as a function of distance from hot gas interface.