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

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Introduction:

Thermal Barrier Coatings (TBCs) are used in industry to increase the operation temperature limits of turbine blades and therefore efficiency. Due to coefficient of thermal expansion mismatch, stress occurs during temperature change and can cause TBCs to spall. Experimental results show that vertical cracks within a TBC offer strain tolerance [1-5]. Influence of crack geometry on TBC thermal and mechanical properties is not well understood. This simulation considers how crack-to-crack distance, crack width, and crack depth influence performance characteristics of TBCs.

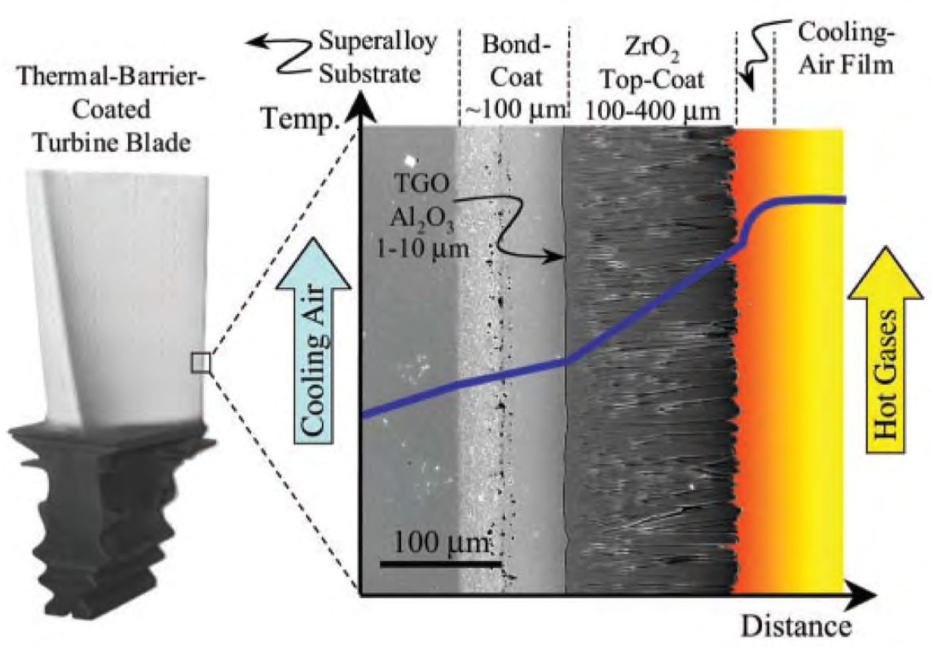

Figure 1 :Cross-sectional view of a TBC over turbine blade [5]

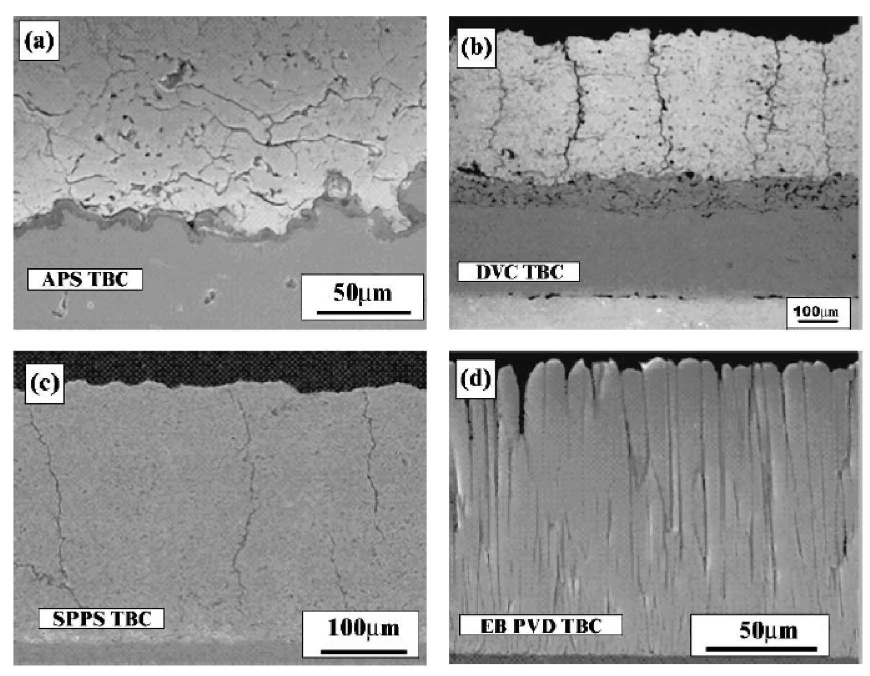

Figure 2 : Comparison of (a) traditional plasma sprayed TBC (b&c) TBC with vertical cracks (d) EB-PVD TBC [1]

Computational Methods:

- COMSOL 4.2a
- Thermal Stress and Heat Transfer in Porous Media modules
- 2D turbine blade section with stacked environmental barrier coating (EBC) and thermal barrier coating (TBC)
- External forced convection on top (combustion gases) and bottom (internal cooling)
- Crack parameters:
  Inter-crack distance 90-800 µm
  Depth half or full thickness
  Width 4 µm or 2 µm
- Steady state analyses include temperature, stress, strain energy density
- Analyses conducted per layer and also at TBC-EBC and EBC-substrate line interfaces. Interfacial analyses in center of boundaries, 3 cracks away from edge on each side.

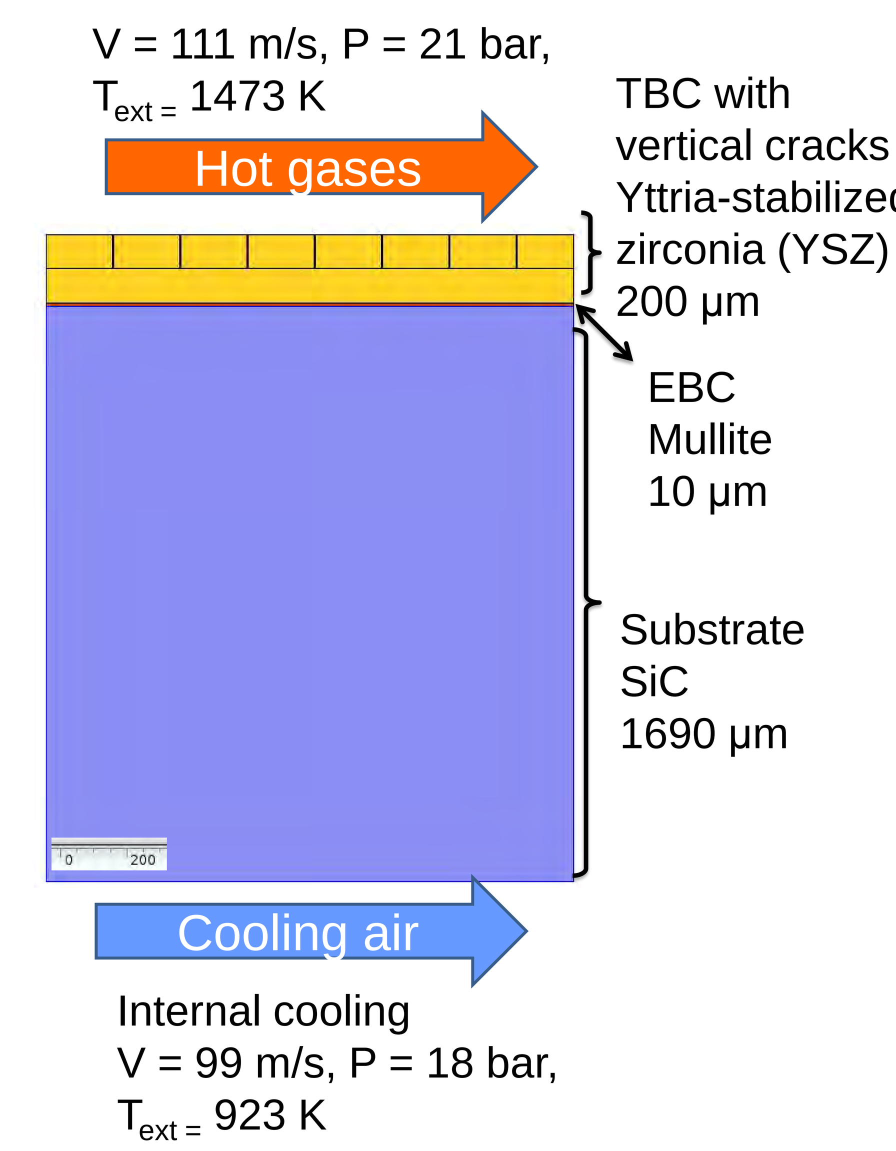

Figure 3 : COMSOL model

Results:

Temperature

Temperature profile shows expected TBC pattern (fig 4) and decreases with greater crack distance (fig 5). Half thickness cracks show lower temperature than full thickness.

Stress and Strain Energy Density

As crack distance increases, max stress within YSZ increases but average stress decreases. More cracks relieve YSZ max stress as expected (fig 6), but more frequent and deeper cracks increase average temperature (fig 5) and therefore average thermal stress (fig 7).

Interfacial stress between YSZ and mullite suggest optimization between mechanical stress relief (prefers more cracks) and thermal stress (prefers less cracks) (fig 8).

Strain energy density trends consistently with stress for all reported analyses.

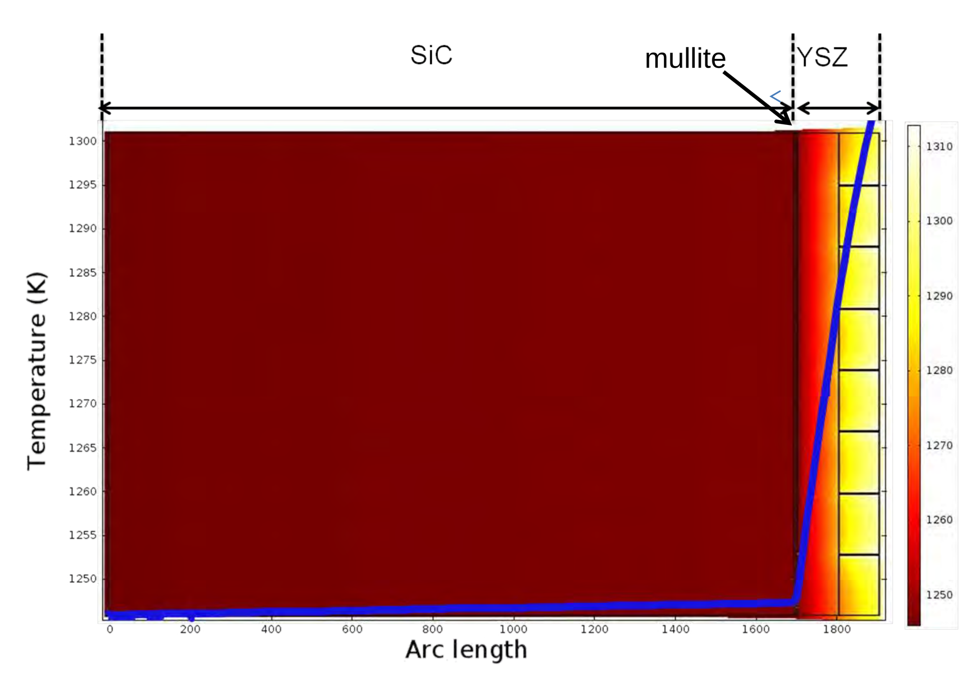

Figure 4: Temperature decreases rapidly through TBC

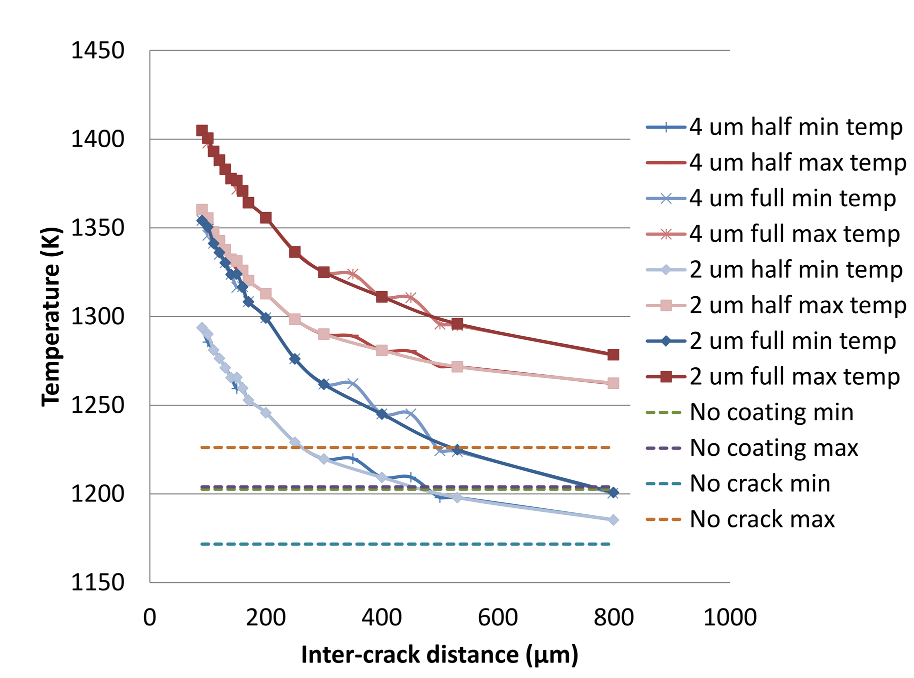

Figure 5: Temperature vs inter-crack distance

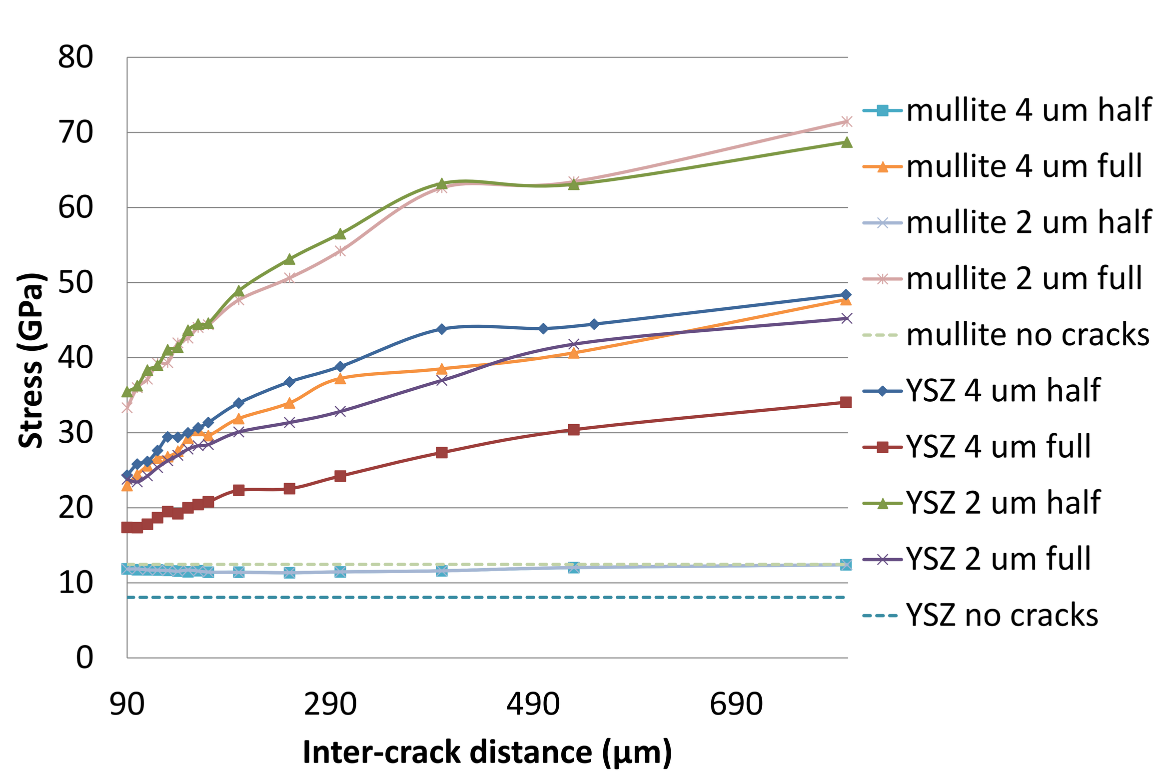

Figure 6: Maximum stress for YSZ and mullite vs inter-crack distance

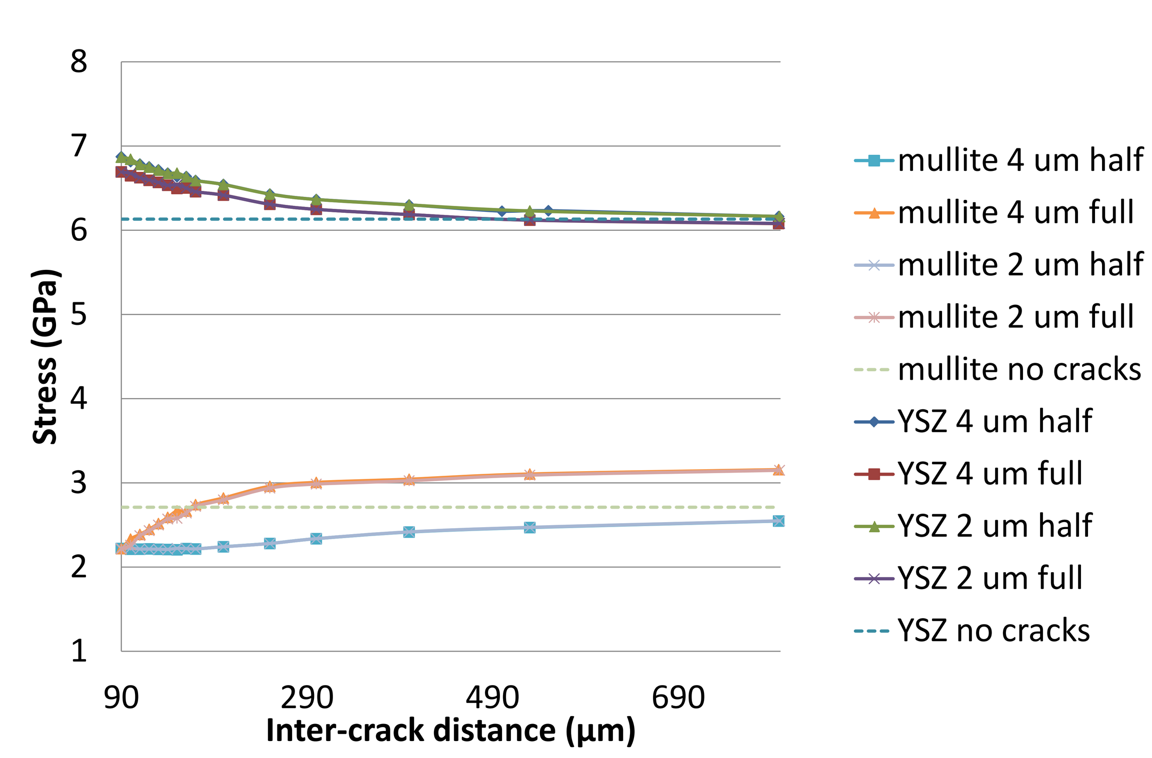

Figure 7: Average stress for YSZ and mullite vs inter-crack distance

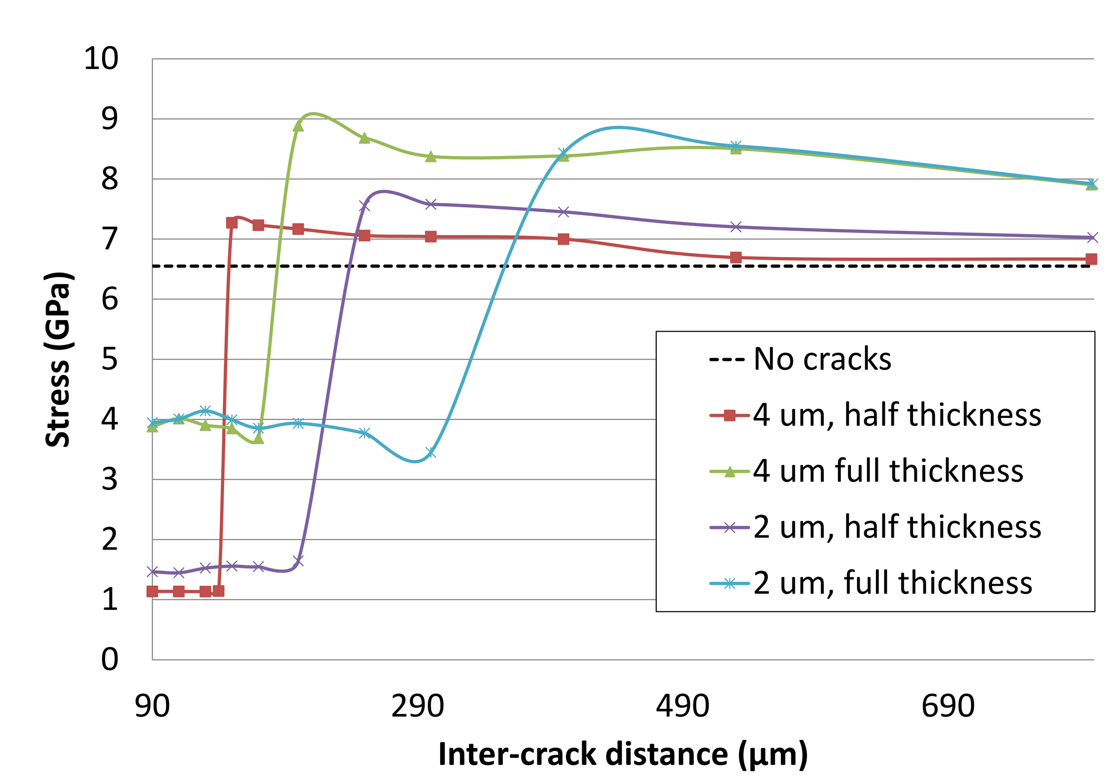

Figure 8: Average YSZ-mullite interfacial stress vs inter-crack distance

Boundary conditions

If boundary conditions exclude forced convection within cracks, temperature and stress are both minimized with decreasing crack distance (fig 9-10).

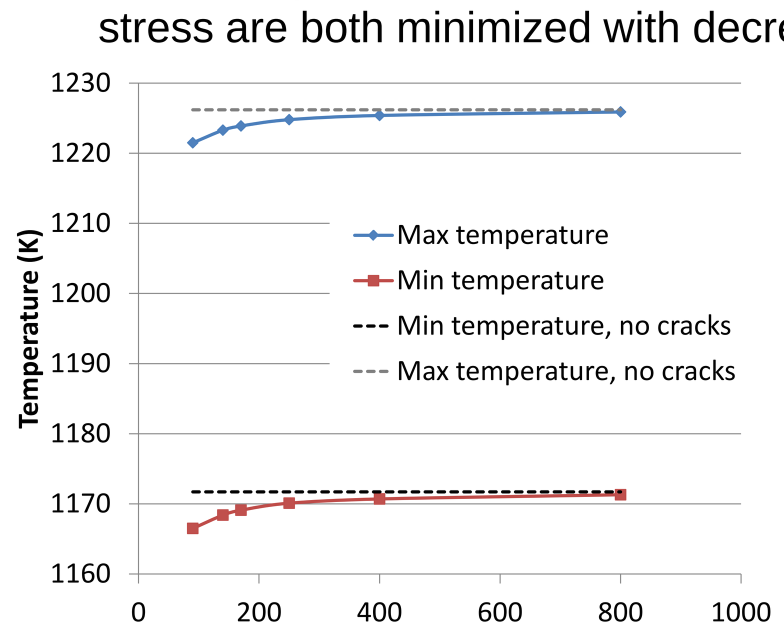

Figure 9: Temperature vs crack distance for no external convection in cracks

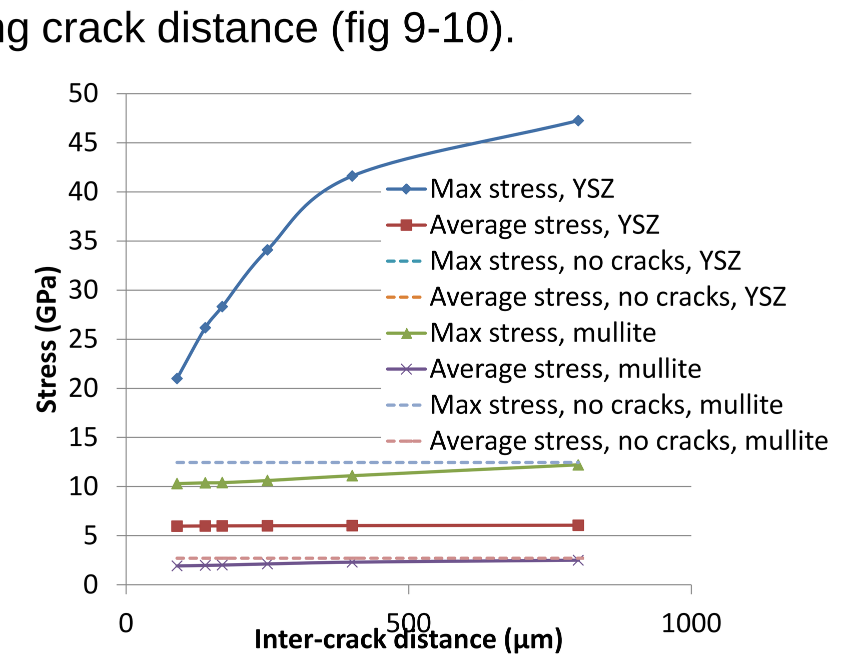

Figure 10: Max and average stress for no external convection in cracks

Conclusions:

- Crack geometry and boundary conditions strongly influence performance characteristics of a TBC-EBC system.
- When convection within cracks is considered, the stress-relieving benefits of more cracks is offset by additional thermal stress. A regime of lower TBC-EBC interfacial stresses occurs as a compromise between these trends. Additionally, half thickness cracks result in less heating and thus less stress than full thickness cracks.
- When forced convection within cracks is ignored, the TBC behaves more ideally in decreasing sample temperature, while the mechanical stress-reduction function of cracks is preserved. More frequent and deeper cracks thus reduce both maximum and average coating stresses.
- Optimization of crack geometries in TBC-EBC systems is a complex problem and depends considerably on expected operating conditions of the turbine blade.
- Further simulation work on crack geometry and coating characteristics is ongoing.

Acknowledgements:

Thank you to Professor Dan Cole for useful discussion.

References:

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