Presented at the COMSOL Conference 2009 Milan

Finite Element Analysis of Thermal Fatigue in Thermal Barrier Coatings (TBC)

C. Borri, A. Lavacchi, A. Fossati, I. Perissi and U. Bardi

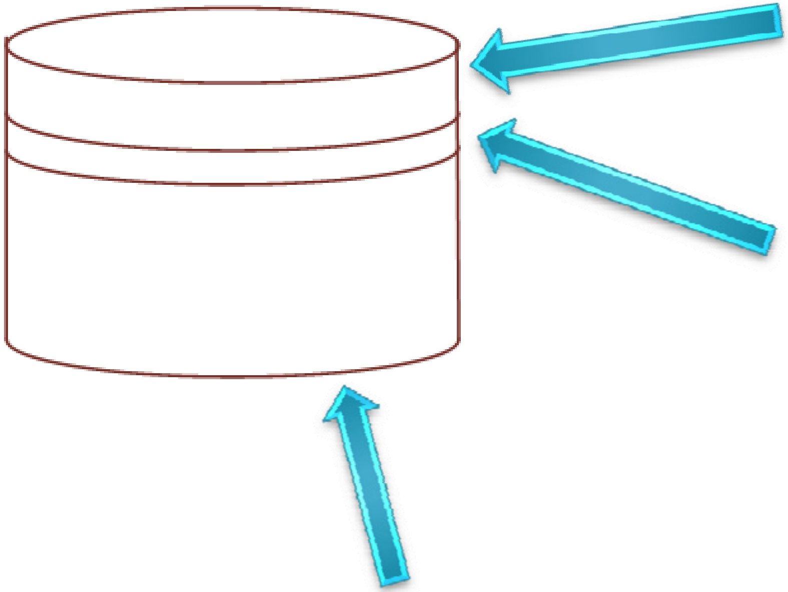
University of Florence – Chemistry Department – Via della Lastruccia 3, Sesto Fiorentino 50019 Firenze

Introduction

- Description of TBC’s and thermal cycling experiments
- Overview of the convective heat transfer characteristic of an impinging air jet
- Assessment of the Thermal-Structural interaction model with COMSOL® multiphysics
- Results of the simulations
- Model validation through temperature measurements on real samples

Thermal Barrier Coatings

- Used to protect metallic substrates from corrosion
- Used in energy and aero-spatial applications



Yttria-Stabilized Zirconia 8% (YSZ)

-Provides thermal stability

MCrAlY Bond Coat (BC)

M= Co, Ni, Fe

-Provides protection against substrate oxydation

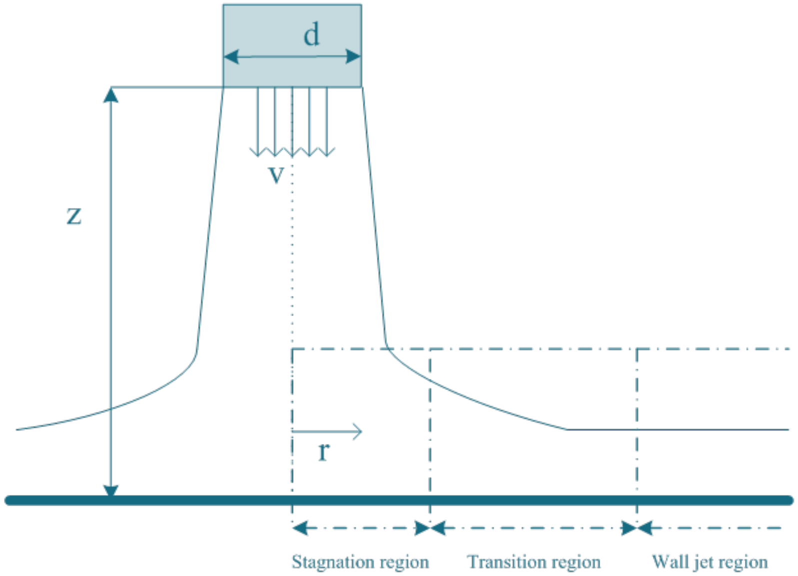
Inconel 718 Substrate

Thermal Cycling Experiments

- Used to predict the TBC’s lifetime and durability
- Samples are warmed in a furnace and then rapidly cooled with a bath or with an impinging air jet
- TBC’s failure is related to the stresses induced by different thermal expansion coefficient of the layers: cracking and delamination processes occur
- Results are largely affected by experimental set up

Use of FEM to assess the Thermal Cycling Experiments

Heat transfer characteristic of the jet



- **Stagnation region heat transfer coefficient [1]:**

$$\frac{Nu}{\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}} = a_1\left(\frac{z}{d}\right)^{-0.11}\left(1-\frac{\left(\frac{r}{d}\right)^{2}\left(\frac{z}{d}\right)^{-0.2}}{b_1}\right)^{1.2}$$

- **Transition region heat transfer Coefficient[1]:**

$$Nu = 0.198\,\mathrm{Re}^{0.6632}\left(\frac{z}{d}\right)^{-0.0826}\left(\frac{r}{d}\right)^{-0.3702}$$

- **Wall jet region heat transfer coefficient[1]:**

$$Nu = 0.0436(E)\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.333}\left(\frac{z}{d}\right)^{0.0976}\left(\frac{r}{d}\right)^{-1.0976}$$

[1] Katti V., Prabhu S.V., International Journal of Heat and Mass Transfer 51 (2008) 4480–4495

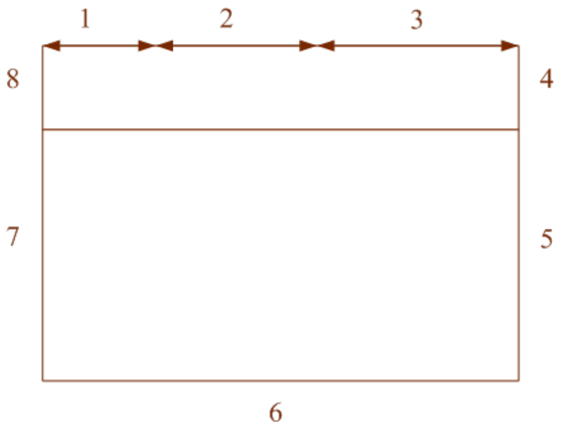
Geometry Reduction for Calculations

- **Geometry was reduced to 2D for symmetry reasons**
- **MCrAlY bond coat was included into the Inconel substrate as they have similar thermo-mechanical properties**

Model Assessment/I

- COMSOL®'s thermal-structural interaction axial symmetry stress-strain with thermal expansion, transient analysis model was used

Boundary Conditions: **Thermal Analysis** **Stress-Strain Model**



1-4, 6 Heat Flux

$$k\nabla T = h\Delta T + h_r \Delta T^4$$

5 Thermal insulation

7, 8 Axial Simmetry

} Free Boundaries

Model Assessment/II

Initial Conditions: **Thermal Analysis** **Stress-Strain Model**

1423 K Temperature in all domains

1423 K Strain Reference Temperature

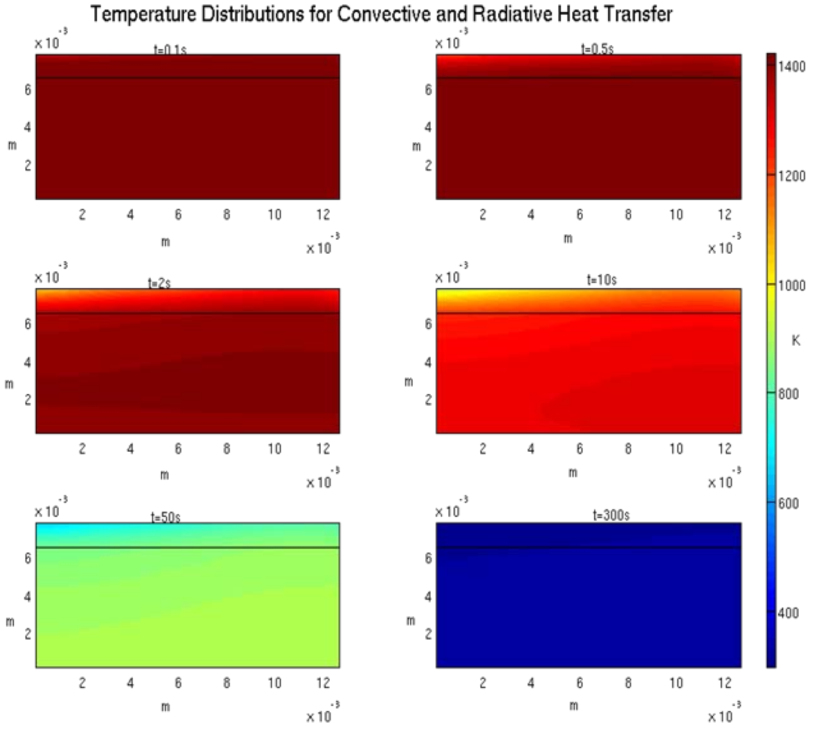
Meshing

Smaller elements at the YSZ-inconel interface and in the stagnation point

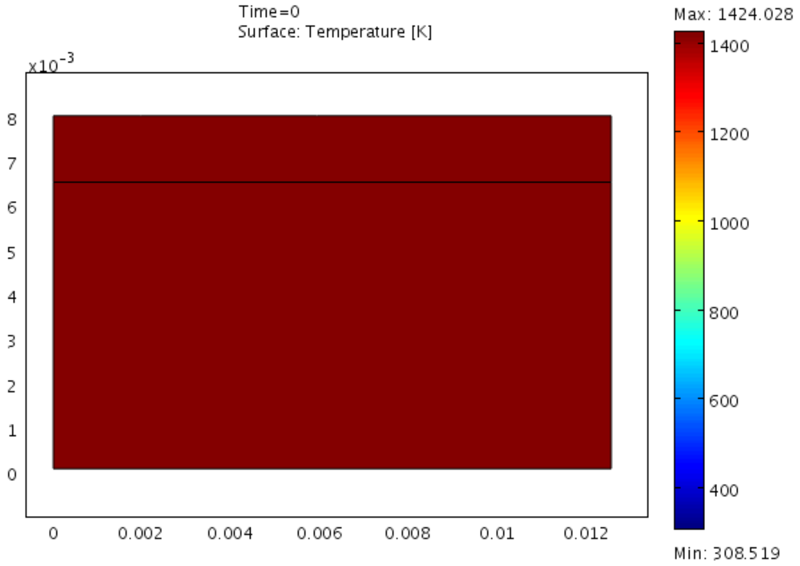
Thermo-Mechanical properties of the materials

Properties	8%YSZ	Inconel 718
Thermal Conductivity (W/m K)	2.29	15.048
Density (kg/m^3)	6000	8510
Heat Capacity at constant pressure (J/Kg K)	600	652
Poisson's Ratio	0.23	0.3
Young's modulus (Pa)	$2.05\cdot10^{10}$	$2\cdot10^{11}$
Thermal expansion coefficient (1/K)	$1\cdot10^{-5}$	$1.15\cdot10^{-5}$

Thermal Analysis Results

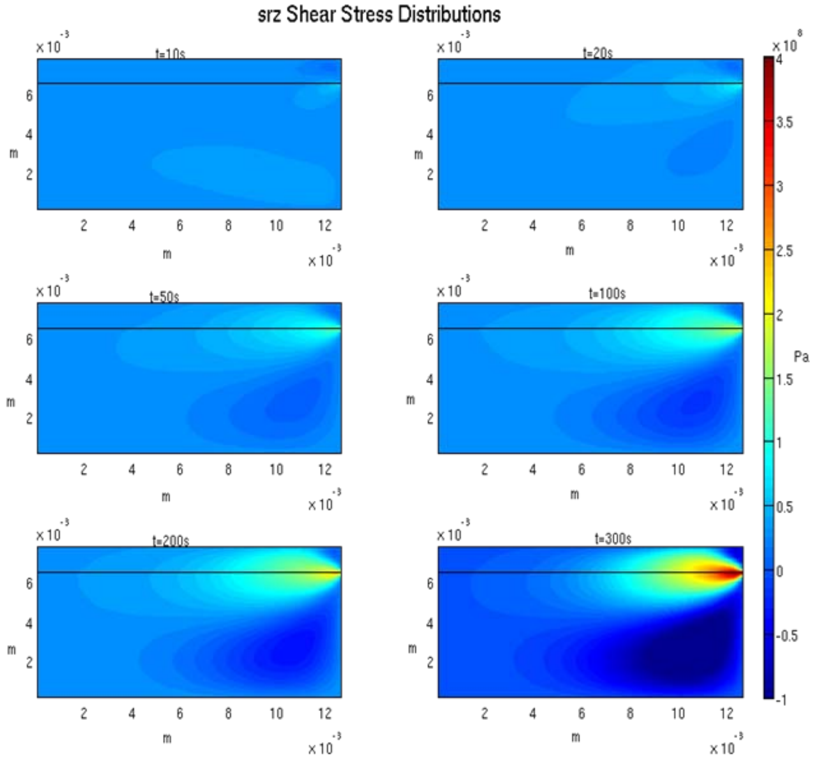


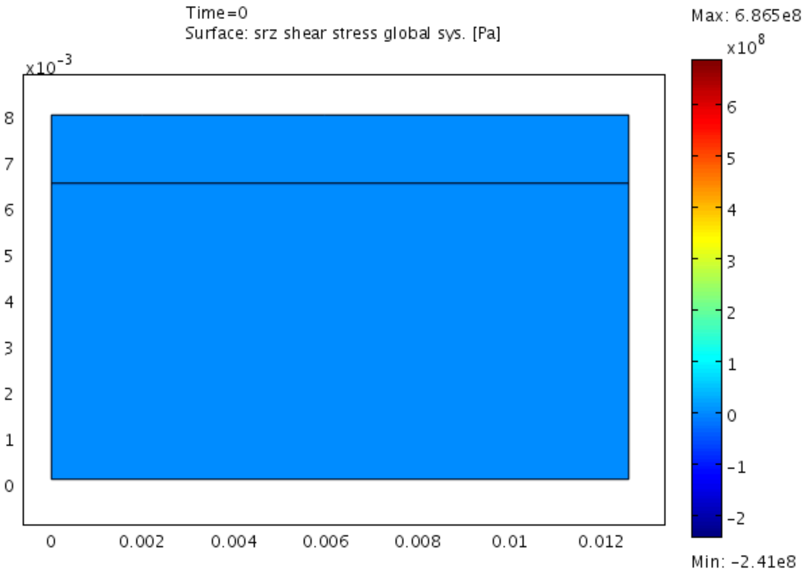
Temperature Distributions for Convective and Radiative Heat Transfer



- **Sample reaches homogeneous temperature after about 300 seconds of cooling**

Stress-Strain Results/I

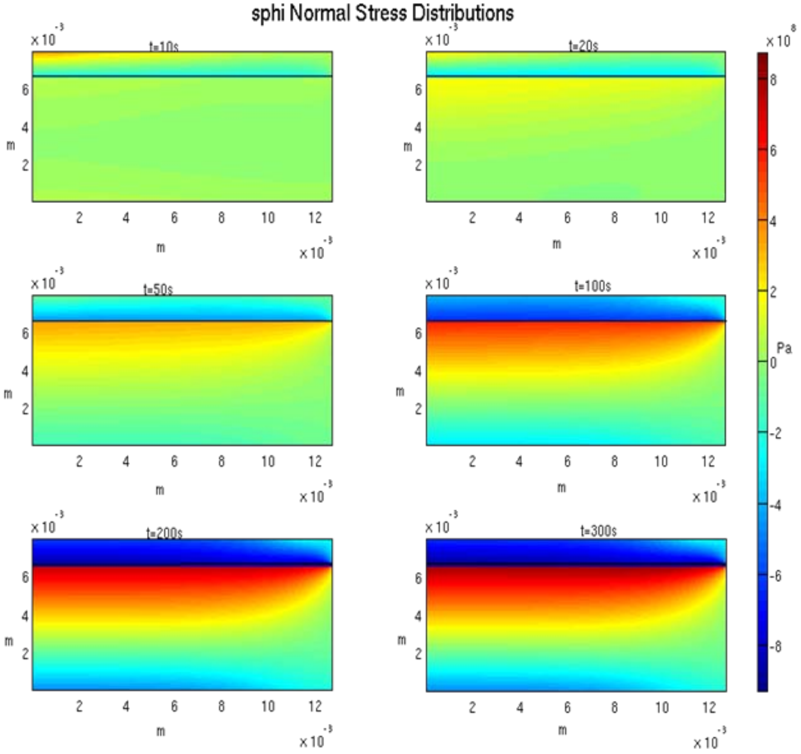


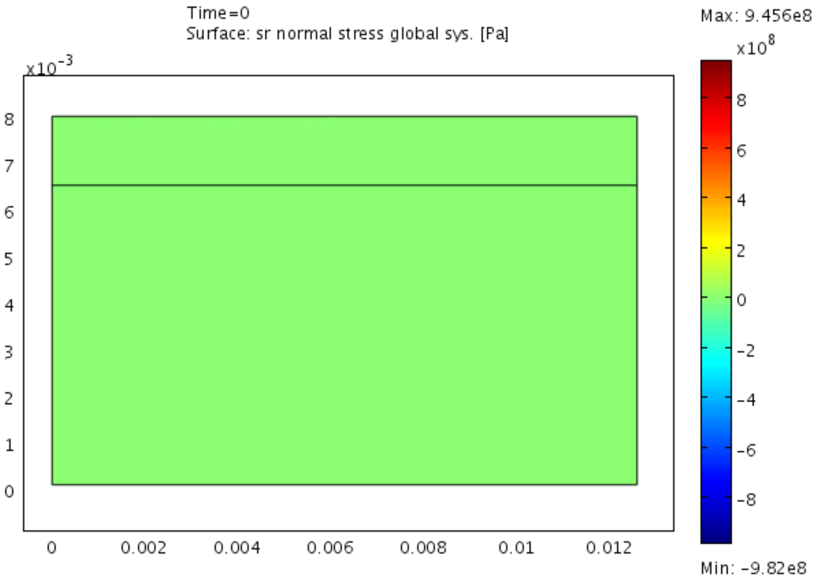


- **Shear stress is responsible for the delamination processes of the sample[2]**

[2] H.Bhatnagar, S.Ghosh, M. E. Walter, International Journal of Solids and Structures 43 (2006) 4384–4406

Stress-Strain Results/II



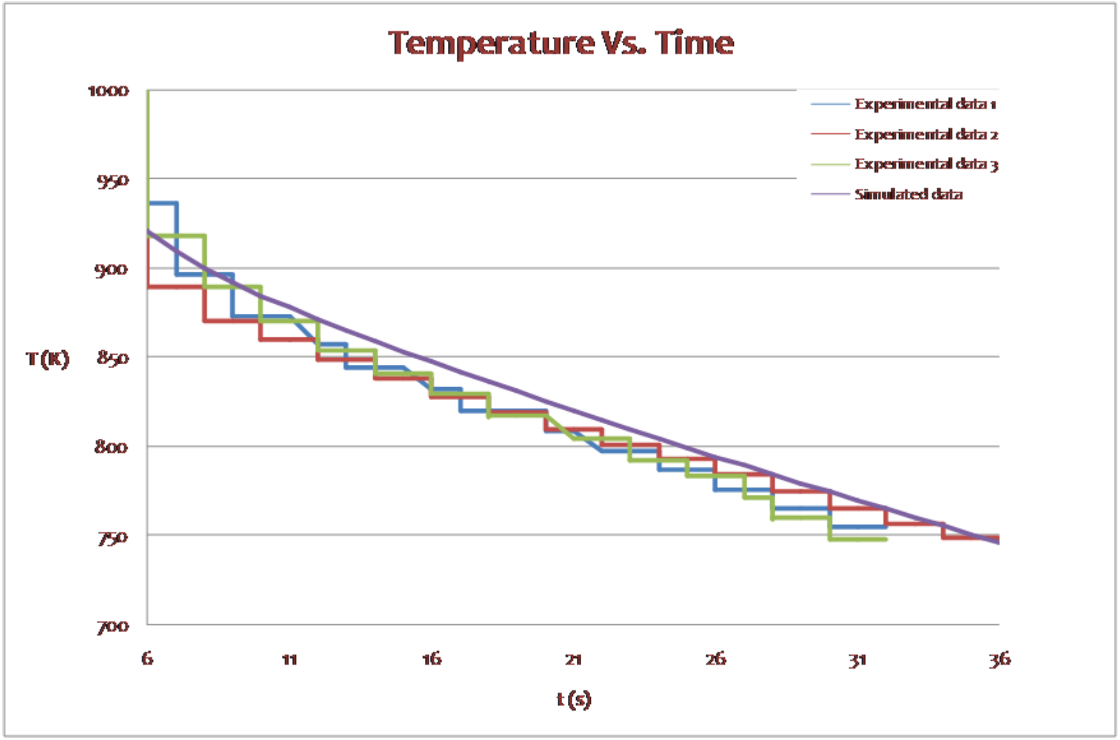


- **Normal stress is responsible for the spallation processes of the sample**[2]

[2] H.Bhatnagar, S.Ghosh, M. E. Walter, International Journal of Solids and Structures 43 (2006) 4384–4406

Validation of the model

- **Comparison between simulated data and temperature measurements with an infrared pyrometer on the point between the transition region and the wall jet region shows good agreement**



Conclusions

- We assessed a finite element model to predict the stress generation during the cooling of a TBC under an impinging air jet

- Simulations show that the stresses are generated on the first 200 seconds of cooling

- Simulation show that the sample is completely cooled after about 300 s of cooling

- The thermal analysis' results show good agreement with the temperature measurements on real samples made by an optical pyrometer

- This kind of study could be a useful tool to predict the sample behavior during the cooling and could help to design more efficient thermal cycling experiments.

Thanks for your attention!

Questions are Welcome!