In-situ Synchrotron Analysis of Thermal Barrier Coatings under Thermal Gradients and Mechanical Loads

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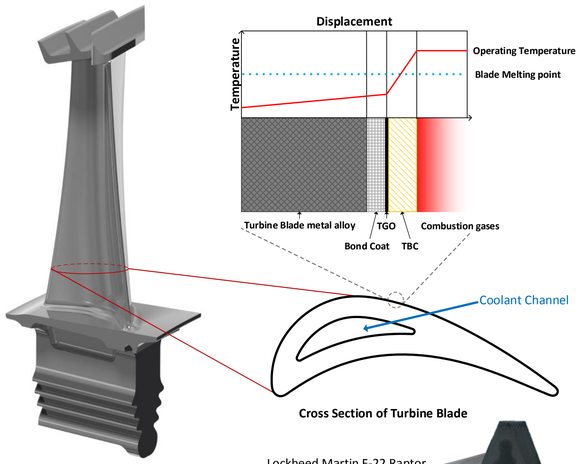
Introduction

There is an increasing need to extend the operational temperature limits of turbine components. Thermal barrier coatings combined with internal substrate cooling allow for operating temperatures exceeding the melting temperatures of the turbine substrate. The thermal expansion mismatch between the different materials however, result in large residual stresses that are linked to failure. In-situ synchrotron diffraction provides the means to establish the evolution of strain at high resolution.



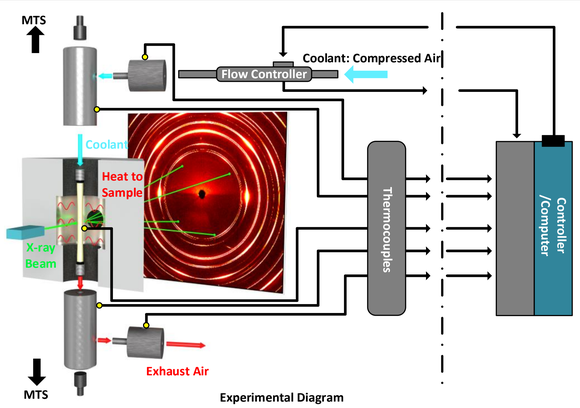
The thermal barrier coating (TBC) is adhered to the surface of the turbine blade by a nickel based bond coat and the blade is forced cooled with air by an internal coolant channel.

Objectives

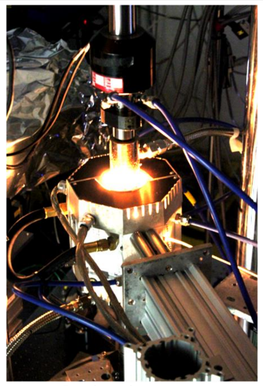
- Develop techniques to apply thermal gradient and mechanical loading while maintaining access to high energy x-ray measurements
- Develop measurement techniques to accurately obtain in-situ X-ray diffraction (XRD) strain measurements of each internal layer of the tubular sample
- Determine strain behavior of coating layers under thermal gradient and mechanical loading conditions

The experiment was conducted at Argonne National Laboratory

Synchrotron X-ray Measurement Techniques

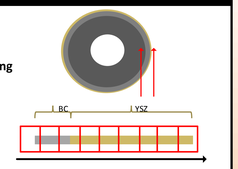


Experimental Diagram

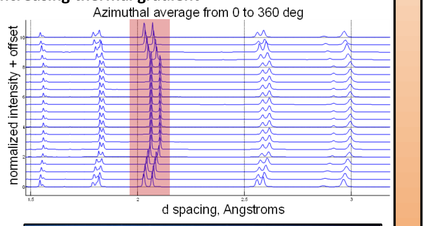


Experiment in progress

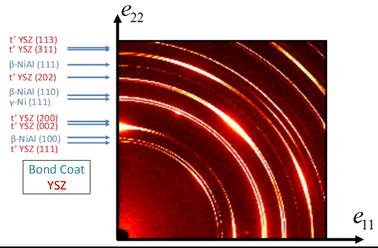
- X-Ray Scan Through Coating Thickness
- Window Size 30 x 300 microns
- 10 Window Scan



Plot of d spacing vs intensity of material peaks scanned with the highlighted section showing the thermal expansion of the bond coat due to the increasing thermal gradient



- The X-rays diffract onto a high resolution 2-D detector in the form of distorted rings
- The elliptical state of the ring is indicative of strain



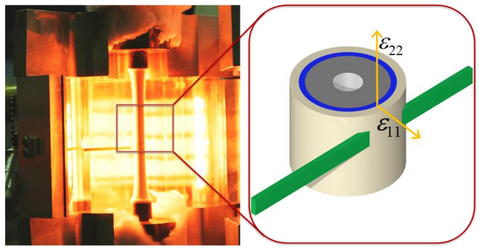
Sample

- IN 100 Substrate
  - Outside Diameter = 8mm
  - Inside Diameter = 4mm
- NiCoCrAlY Bond Coat
  - 80 µm EB-PVD Coating
- α-Al2O3 Oxide Layer (TGO)
  - As-Coated 0.5 µm Thickness
- Yttria Stabilized Zirconia (YSZ)
  - EB-PVD 240 µm Coating

Cylindrical sample manufactured at DLR

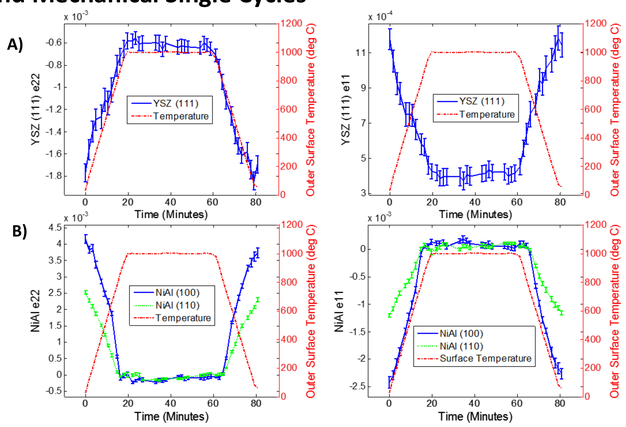
Results

Thermal Gradient and Mechanical Single Cycles

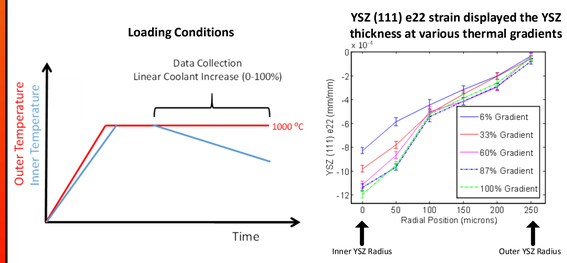


Orientation of e22 and e11 with respect to the sample

- A) At room temperature, YSZ expresses compressive in-plane strain (e22)
- B) The bond coat expresses tensile in-plane strain (e22)
- As the surface temperature is ramped up to high temperature, both layers then relaxes to zero strain

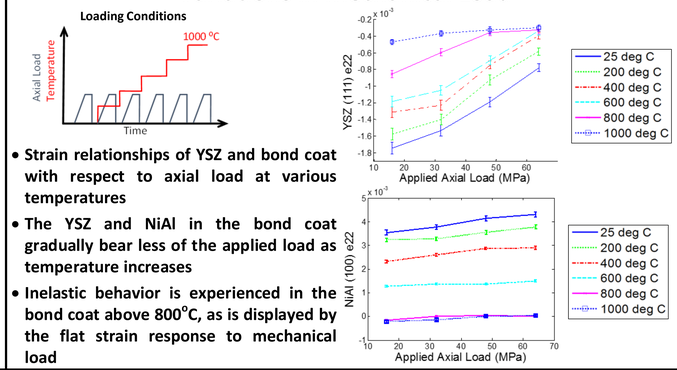


Variations in Thermal Gradients



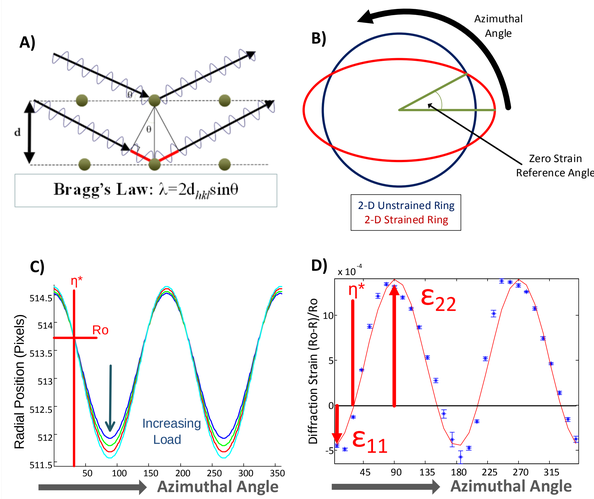
- With increasing thermal gradient, the YSZ demonstrates minimal change in strain from the outer surface into the middle of the layer
- The inner region of the YSZ displays a significantly increasing compressive strain and thus higher strain gradient

Variations in Mechanical Load



- Strain relationships of YSZ and bond coat with respect to axial load at various temperatures
- The YSZ and NiAl in the bond coat gradually bear less of the applied load as temperature increases
- Inelastic behavior is experienced in the bond coat above 800°C, as is displayed by the flat strain response to mechanical load

Analysis



A) When strain is induced on a lattice structure, the diffraction angle is altered due to Bragg's Law

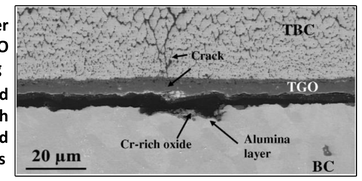
B) The change in diffraction angle results in an elliptical distortion of the diffraction ring

C) Identifying the zero strain reference angle

D) Bond coat strain results at an individual measurement for the experiment with a 128Mpa load and 40 liters/min flow rate

Future Work

- Aged samples have a thicker and more developed TGO layer due to repeated cycling
- Analyze strains in aged samples to establish quantitative strain relief and observe damage mechanisms



Crack formation in an aged sample, by M. Bartsch et al., 2008

References

- K. Knipe, A. Manero, S. Siddiqui, C. Meid, J. Wischek, J. Okasinski, J. Almer, A. Karlsson, M. Bartsch, and S. Raghavan, "Effects of Thermal Gradient and Mechanical Loading on In-Cycle Strains for Thermal Barrier Coatings Determined through Synchrotron XRD Measurements", (*In Review*)
- M. Bartsch, B. Baufeld, S. Dalkiliç, L. Chernova, M. Heinzelmann, "Fatigue cracks in a thermal barrier coating system on a superalloy in multiaxial thermomechanical testing" *International Journal of Fatigue*, 30(2008), p. 211
- S. Siddiqui, K. Knipe, A. Manero, C. Meid, J. Wischek, J. Okasinski, J. Almer, J. Schneider, M. Bartsch, S. Raghavan, "Synchrotron X-ray Measurement Techniques for Thermal Barrier Coated Cylindrical Samples" *Rev Sci Instrum*, 84(2013), p. 8

Acknowledgements

- This material is based upon work supported by the National Science Foundation grants (Grant Nos. OISE 1157619 and CMMI 1125696) and by the German Science Foundation (DFG) grant (Grant No. SFB-TRR103), Project A3
- Use of the Advanced Photon Source at Argonne National Laboratory was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357