Project ID: PM024

NDE DEVELOPMENT FOR ACERT ENGINE COMPONENTS

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DOE Annual Merit Review, June 7-11, 2010

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Overview

Timeline

- Project start: Oct. 2007
- Project end: Sep. 2011
- Percent complete: 55%

Budget

- Total project funding
  - DOE: $800k
- Funding received in FY09
  - $200k
- Funding for FY10
  - DOE: $200k

Collaborators

- Caterpillar, Inc.
- ORNL

Barriers

- Barriers addressed:
  - Inadequate test standard and durability data for widespread use of advanced materials
  - Materials for hot-section and engine structures to meet engine life greater than 1 million miles
  - Nondestructive techniques are not sufficiently developed
- Target:
  - By 2015, develop supporting materials technologies to improve heavy-duty engine efficiency to 50% while meeting emission standards (*Goals from Multi-Year Program Plan March 18, 2010*)

Objectives

- Develop rapid, reliable, and repeatable nondestructive evaluation (NDE) methods for inspecting advanced materials and processing technologies to support the material enabled high efficiency diesels program (ACERT program)

C-15 ACERT engine
(image provided by Caterpillar)

- Develop/establish NDE methods and procedures to characterize advanced thermal barrier coatings (TBCs), friction stir processed surfaces, friction welding, and heat recovery materials etc in:
  - thermal management components
  - structural components
  - valvetrain components
  - other components

Milestones

- Establish NDE procedure and detection sensitivity and evaluate candidate TBC-coated exhaust components – Sep. 2009
  - Both thermal imaging and optical scanning methods were evaluated
- Investigate synchrotron x-ray CT technologies for NDE characterization of advanced materials for diesel-engine applications – Dec. 2009
  - Micro x-ray CT for microstructural analysis of ceramics
  - High-energy x-ray CT for NDE characterization of light-weight metallic components for diesel engines
- Develop/assess NDE technologies for characterization of the quality of as-processed and the performance and durability of bench- and engine-tested thermal barrier coatings – Sep. 2010

Approach

- Working with ACERT Program team (Caterpillar and ORNL), investigate NDE methods for inspecting various advanced diesel engine materials/components
  - NDE methods for ceramics, valves, joints
  - NDE methods for TBCs for ACERT exhaust system

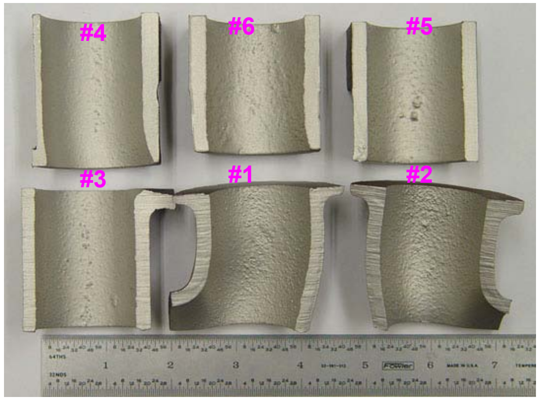
- Current NDE development is focused on infrared thermal-imaging and optical scanning methods for characterization of TBCs
  - Thermal imaging is the primary NDE method for TBCs
    - *3D thermal tomography imaging of TBC structures and damage*
    - *Quantitative measurement of thermal properties of TBCs*
  - Optical scanning detection of TBC flaws and delaminations
  - NDE inspection of coating samples in conditions:
    - *As-processed*
    - *Thermal-cycling tested*
    - *Engine tested*

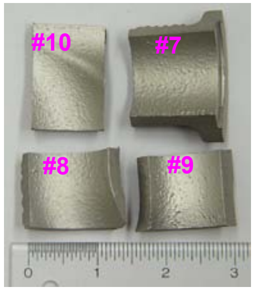
Technical Accomplishments/Progress

- Developed thermal imaging technology for NDE characterization of as-processed and thermally-cycled TBCs
  - System setup and test procedure was established for testing oxidation-resistant TBCs considered for exhaust manifold applications
  - Initial thermal imaging sensitivity was established
  - TBC coupon samples in as-processed and thermal-cycled conditions were tested; delaminations due to thermal cycling were detected
- Demonstrated capability of optical NDE technologies for high-resolution detection of flaws and delaminations in TBCs
  - Small flaws and delaminations in the order of tens of microns were detected in TBC coupon samples
- Evaluated synchrotron x-ray CT technologies for NDE inspection of advanced materials and components for diesel engines
  - MicroCT was evaluated for detection of submicron cracks in ceramics
  - High-energy CT was used to inspect large metallic parts

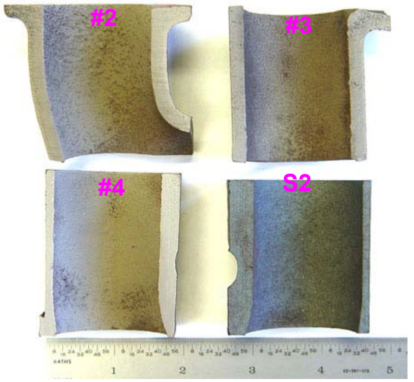
TBC Coupons for Exhaust System

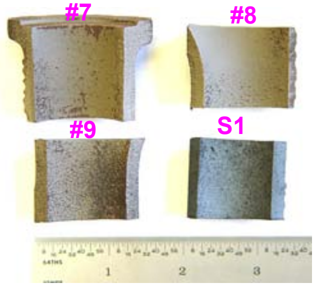
As-Processed TBCs



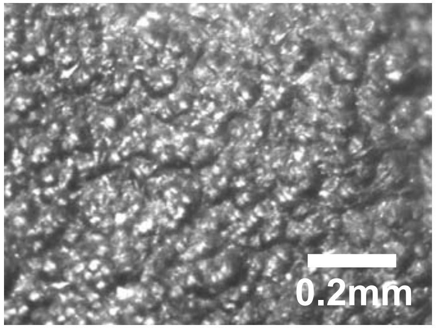


Thermally-cycled TBCs





Surface Micrographs



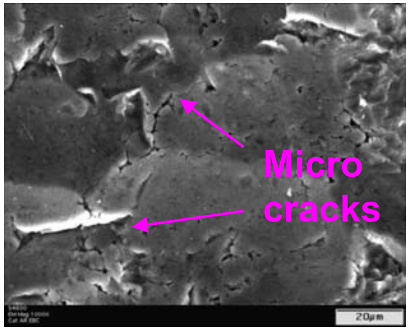
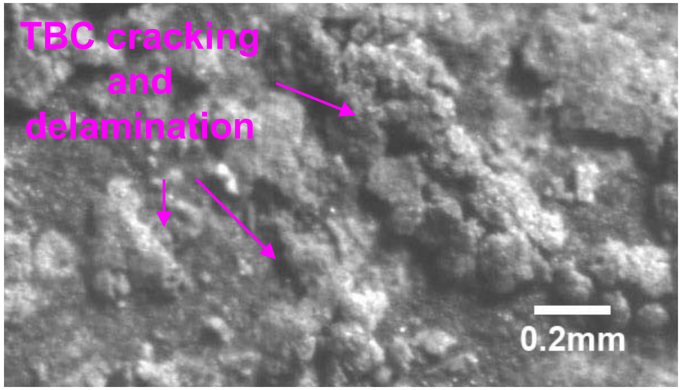


Image from Dr. HT Lin of ORNL

Surface Micrograph



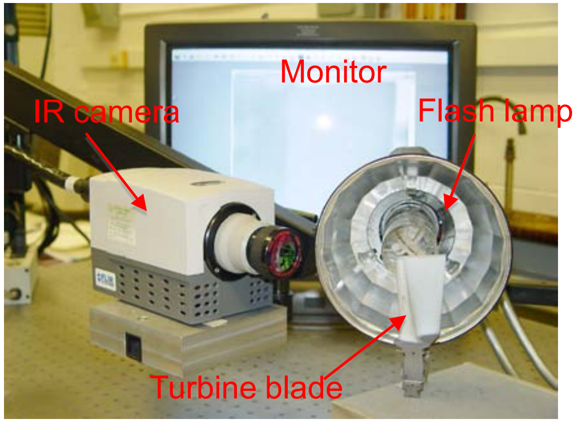
- As-processed TBC is generally uniform and covers the entire substrate surface
  - Small coating cracks exist
  - TBC thickness is ~100μm thick (ORNL)

- Thermal cycling test was perform at ORNL
  - 500 cycles between 300ºC and 760ºC
- Severe TBC cracking and delaminations are observed from surface

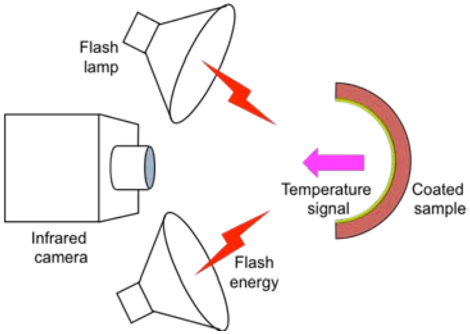
NDE Methods for Characterizing TBCs

Thermal Imaging NDE Method

One-sided thermal imaging system



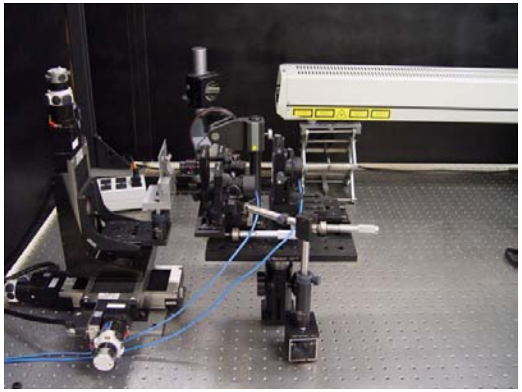
Setup for testing a TBC sample



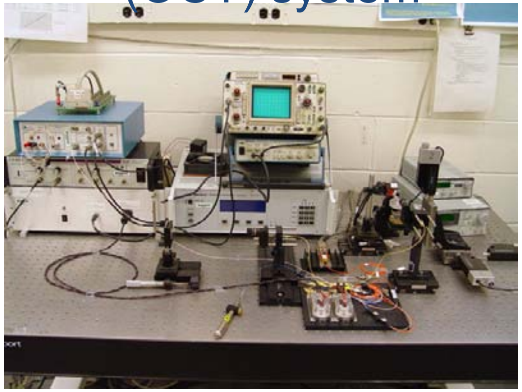
- Thermal imaging inspection of entire TBC surface for all TBCs
  - 3D thermal tomography data analysis

Optical Scanning NDE Methods

Laser backscatter system



Optical coherence tomography (OCT) system

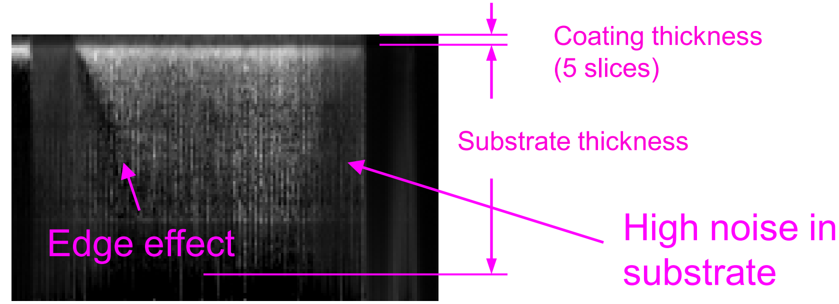


- Optical imaging for examination of detailed TBC microstructure
  - Laser backscatter for area inspection
  - OCT for cross-section inspection

Thermal Tomography of As-Processed TBC

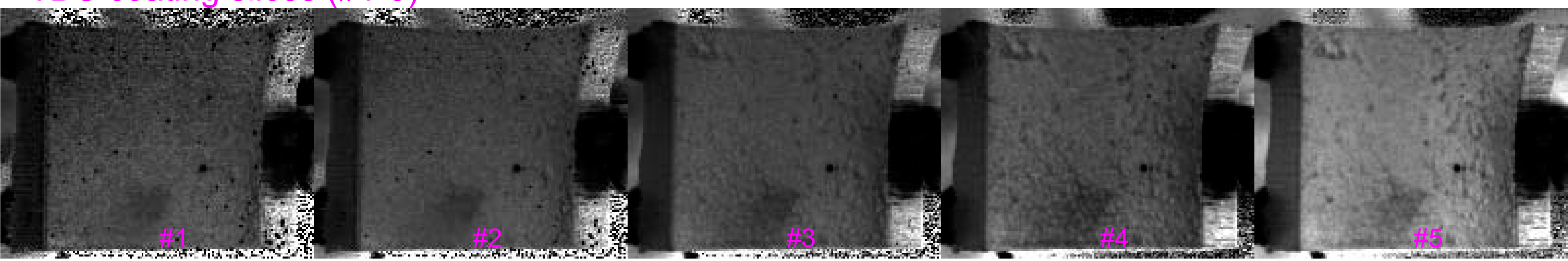
TBC #9 photo

Cross-section slice at J=71

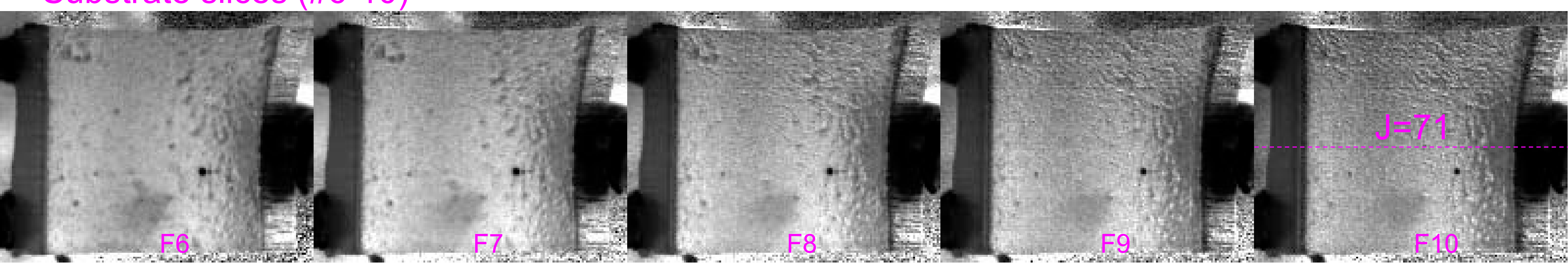


TBC coating slices (#1-5)

Plane slices



Substrate slices (#6-10)

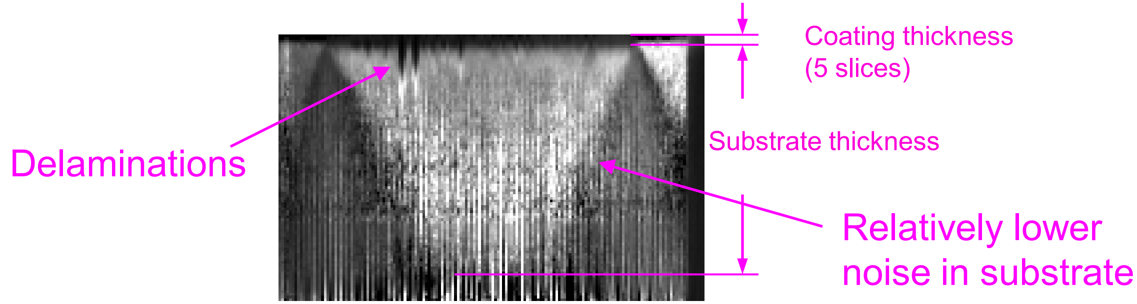


- Plane slices #1-5 are within TBC that has low thermal effusivity; each slice is ~20μm thick
  - Coating is generally uniform without major defects
- Plane slices #6-10 (& deeper) are in the substrate that has higher thermal effusivity
  - Data in substrate are noisier due to low heat absorption on TBC surface

Thermal Tomography of Thermal-Cycled TBC

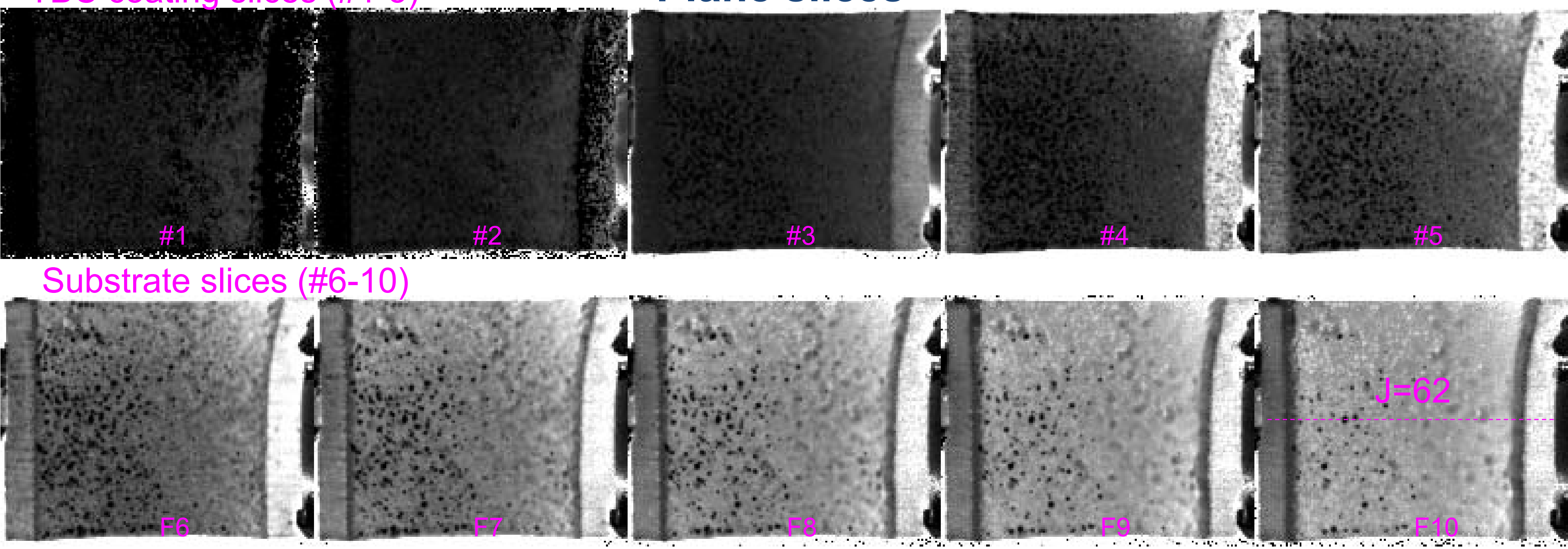
TBC #9 photo

Cross-section slice at J=62



TBC coating slices (#1-5)

Plane slices

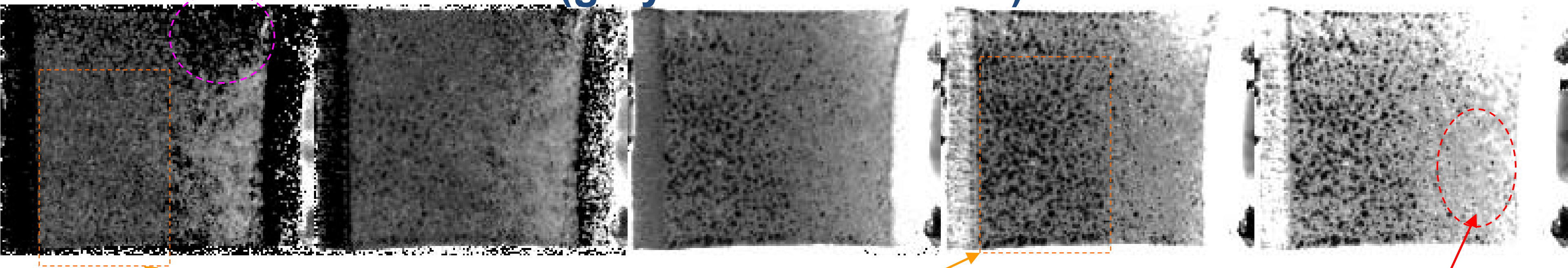


- Coating slices show spots of low effusivity that correspond to delaminations
  - Oxidized coating has better heat absorption in thermal imaging test, so data quality is little better (relatively lower noise in substrate)

NDE Analysis of Thermal-Cycled TBC #9

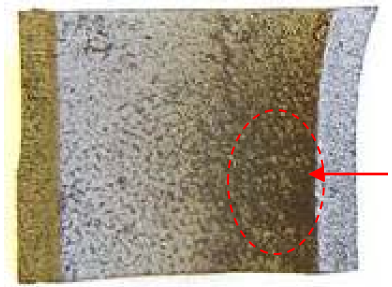
Shallow delaminations

Plane slices #1-#5 within the coating layer (grayscale is rescaled)



Each slice is ~20µm thick

Delaminations (black spots) are not apparent in Slice #1; become most prominent in Slice #4



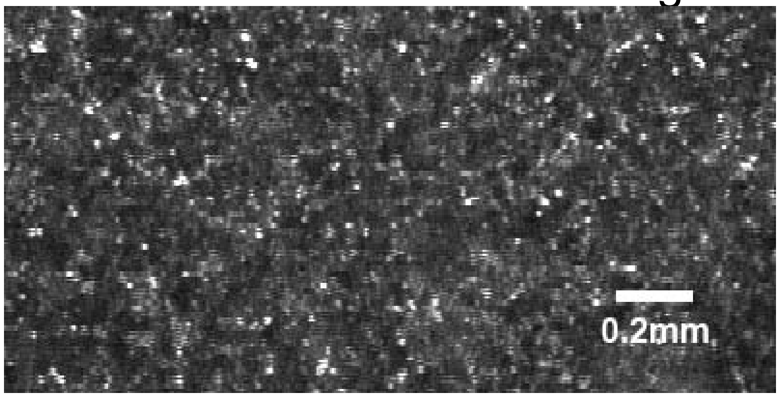
This area has little feature; indicating that delaminated coating had already spalled

- Damages and delaminations are located at different depths
- Detected flaw/delamination depth may be slightly deeper than indicated, because of thermal diffusion effect that affect thermal tomography reconstruction of depth slices
- Detected delamination size is limited by thermal-image pixel size, at ~0.23mm

Optical Imaging Analysis of TBC Surfaces

As-processed TBC surface

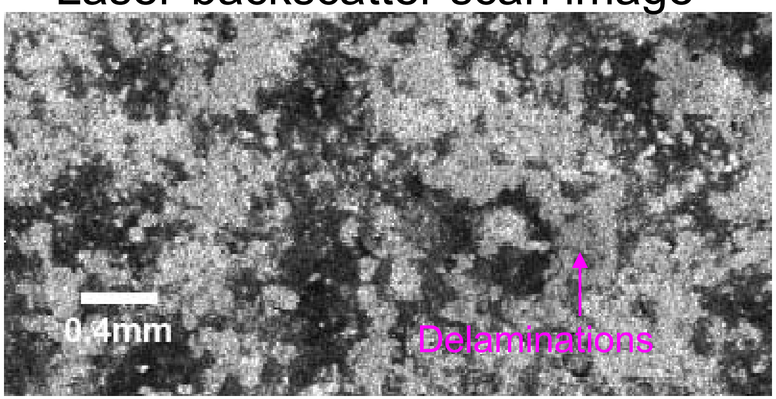
Laser-backscatter scan image



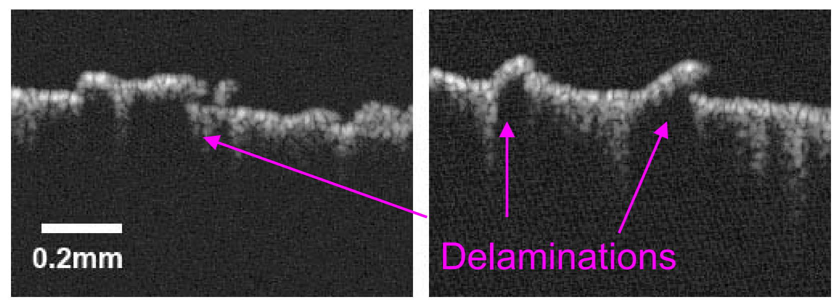
- High scatter spots are detected. Many of the spots form circular patterns of various diameters
- The high-scatter spots are likely microcracks in the coating, with sizes typically <25μm

Thermal-cycled TBC surface

Laser-backscatter scan image



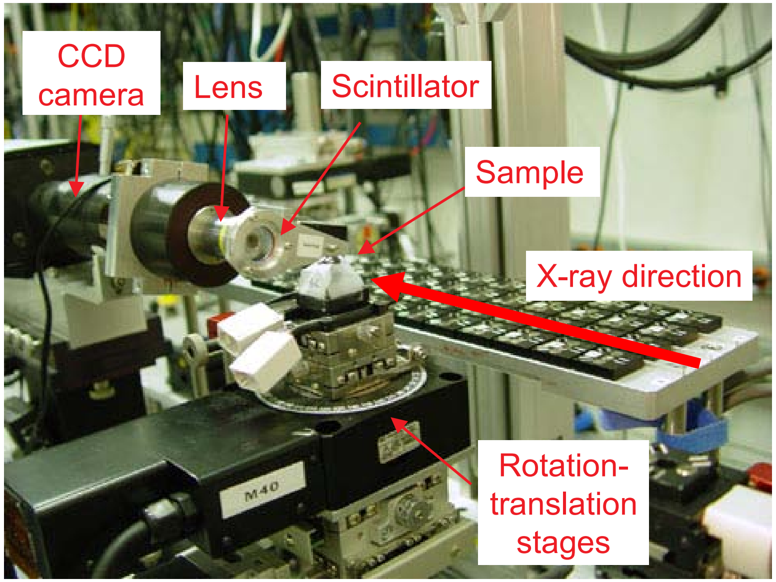
OCT cross-sectional scan images



- Delaminations show high scatter intensity in laser-backscatter image
  - Small delaminations (10-20μm) can be detected
- TBC surface (delamination) topography can be determined from OCT scan images

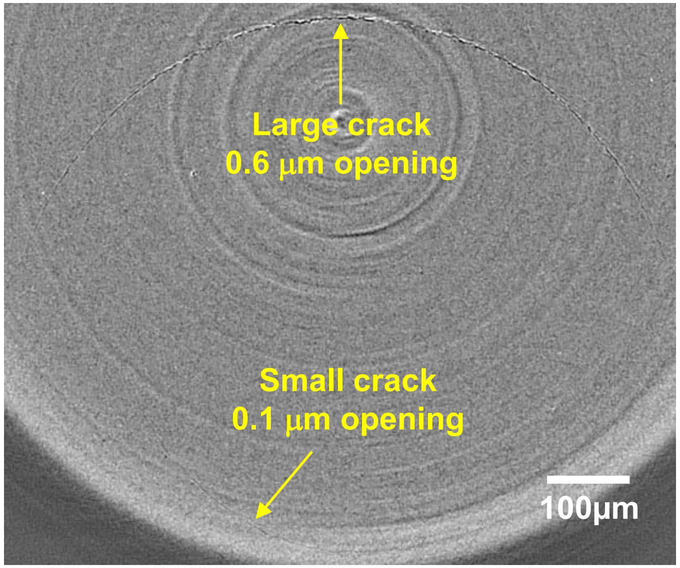
Synchrotron X-Ray CT Methods at APS

MicroCT System at ANL's APS



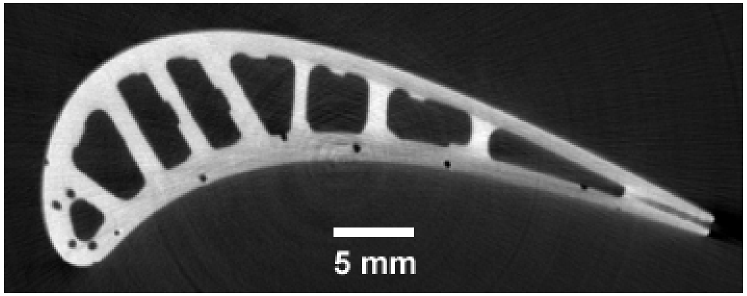
- Synchrotron microCT
  - 3D pixel size at ~1μm
  - Submicron cracks in ceramics can be detected
- High-energy synchrotron x-ray CT
  - X-ray energy >250keV; may penetrate thick metallic components
  - Current pixel size ~40μm

MicroCT slice of ceramic subsurface



Two submicron cracks are detected

High-energy x-ray CT slice of a superalloy turbine blade



Collaborations

- Partners
  - Caterpillar (Industry): Collaboration in material characterization, NDE method evaluation and utilization in industrial applications
  - ORNL (Federal): Collaboration in material testing and characterization, and correlation between NDE and destructive methods

- Technology Transfer
  - Collaborations with researchers at the Center for Thermal Spray Research at Stony Brook University, Harvard University, NASA, and industry to evaluate and validate thermal imaging technologies for TBC characterization and NDE

Future Work

- Continue development of thermal imaging methods for NDE of TBCs for diesel engine applications
  - Improve detection sensitivity and spatial resolution for thermal imaging characterization of TBCs
  - Correlate NDE data between thermal and optical methods
  - Evaluate coating durability under bench and/or engine test conditions
- Investigate NDE methods for thermal recovery materials
- Develop x-ray and ultrasonic imaging methods for inspection of joint components
- Conduct NDE development for inspecting other engine components identified by the ACERT Program team

Summary

- NDE development for engine components made from/by advanced materials/processes is essential to assure their quality and durability to meet engine efficiency and emission goals
- Current NDE development is focused on thermal and optical imaging methods for characterization of oxidation-resistant TBCs for diesel engine exhaust systems
  - Thermal imaging can inspect the entire TBC surface to determine the quality of as-processed TBCs as well as detect and characterize damages/delaminations at various depths in thermal-cycled TBCs
  - Optical methods may detect small flaws and delaminations in TBCs
  - NDE data are being correlated and optimized
- Collaboration with material scientists and engine engineers at Caterpillar and ORNL to develop and apply NDE technologies for critical engine components