NDE Development for ACERT Engine Components

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J. G. Sun
Nuclear Engineering Division
Argonne National Laboratory, Argonne, IL

Collaborators:

Jeff Jensen, Nate Phillips, Nan Yang
Caterpillar, Inc.

HT Lin, Mike Kass, D. Ray Johnson
Oak Ridge National Laboratory

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Overview

Timeline

- Project start: Oct. 2007
- Project end: Sep. 2011
- Percent complete: 25%

Budget

- Total project funding
  - DOE: $800k
- Funding received in FY09
  - $91k so far due to CR
- 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 (by 2012)
  - Nondestructive techniques are not sufficiently developed
- Target:
  - By 2012, develop supporting materials technologies to enable heavy-duty engine efficiency of 55% while meeting emission standards

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)

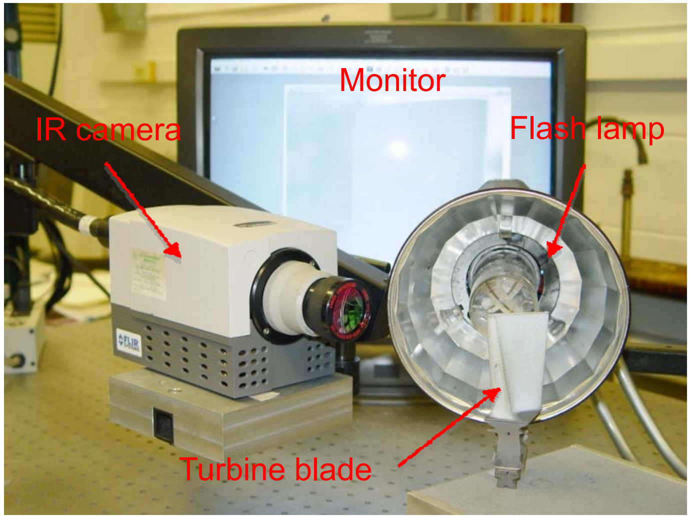
- Establish NDE methods and procedures to characterize advanced materials, coatings, friction stir processed surfaces, friction welding, etc in:
  - thermal management components
  - structural components
  - valvetrain components
  - other components

Milestones

- Investigate various NDE technologies for advanced valvetrain, joining, and coating components for diesel engines. – Sep. 2008
- Identify ACERT™ materials and components for NDE evaluation. – March 2009
  - In coordination with the ACERT™ program, it was determined that oxidation-resistant/thermal-barrier coatings for thermal management components will be used and evaluated in early phase of ACERT™ engine tests.
- Develop and assess NDE methods for characterization of thermal barrier coatings (TBCs). Establish NDE procedure and detection sensitivity and evaluate TBC coated components. – Sep. 2009

Approach

- Working with ACERT™ Program team, investigate NDE methods for inspecting various advanced diesel engine materials/components
  - NDE methods for ceramics, valves, joints
  - NDE methods for thermal barrier coating (TBC)
- Current NDE development is focused on flash thermal-imaging methods for TBC coating characterization
  - TBC coated exhaust components will be evaluated in initial ACERT™ tests
  - To ensure quality and durability, NDE inspection of coating samples in conditions:
    - *As-processed*
    - *Fatigue/bench tested*
    - *Engine tested*



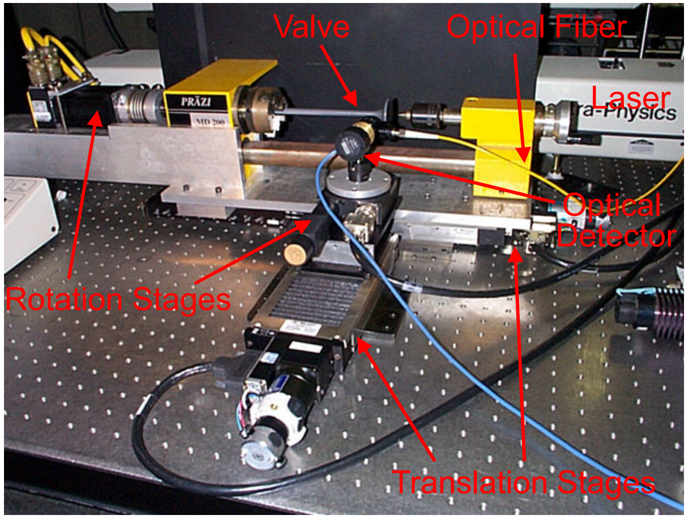
One-sided flash thermal imaging setup for testing of a turbine blade with TBC coating

Technical Accomplishments/ Progress/Results

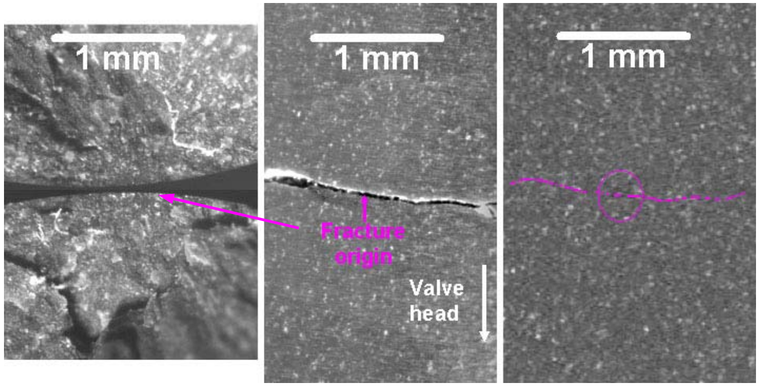
- NDE methods applicable to ceramics, valves, joints, and coatings were investigated (FY2008)
  - Optical scanning methods
  - Ultrasonic scanning methods
  - X-ray imaging methods
  - Thermal imaging methods
- Thermal imaging is being developed as the primary NDE method for characterization of thermal barrier coatings (FY2009)
  - Material systems considered for initial ACERT™ engine evaluation are oxidation-resistant and thermal-barrier coatings for exhaust manifold components
  - Thermal imaging has been widely used for NDE of TBCs on gas turbine components; It is being assessed for NDE of thin and thick coatings for diesel engine components
  - NDE inspection for TBC samples after fatigue/bench test at Caterpillar and ORNL in near term, and for engine-tested samples when available

NDE Methods for Advanced Ceramics

- Laser backscatter was successfully utilized for characterization of machining and service induced damage in ceramic (and intermetallic) engine valves
  - Detection of damage level and fracture initiation flaws
- Optical coherence tomography (OCT) and confocal microscopy may image 3D subsurface microstructure in ceramics and coatings
- Ultrasonic surface acoustic waves based on phased array probes may detect subsurface defects/damages in flat/curved ceramic components



Optical backscatter inspection of valve



Fracture surface Tensile surface NDE image

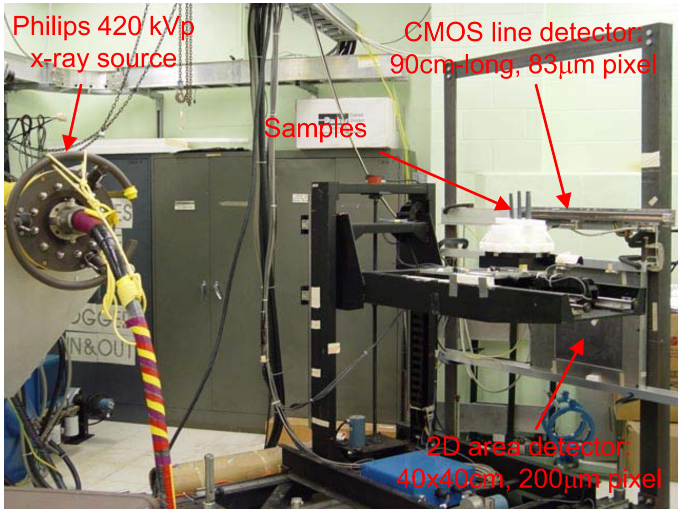
NDE detection of fracture origin (an inclusion) in ceramic valve stem

NDE Methods for Welds/Joints

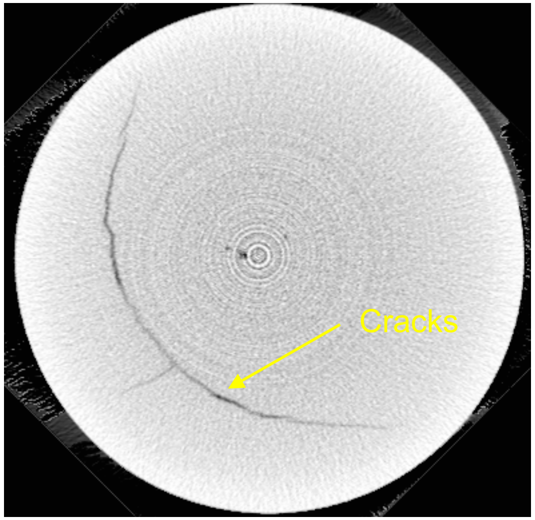
- X-ray radiography and computed tomography (CT)
  - may determine crack configuration & area
  - may lead to prediction of joint strength
  - may achieve high-resolution and high-sensitivity by using synchrotron x-ray CT systems at ANL
- Ultrasonic scanning
  - for standard part quality inspection

Friction welded TiAl turbo wheels

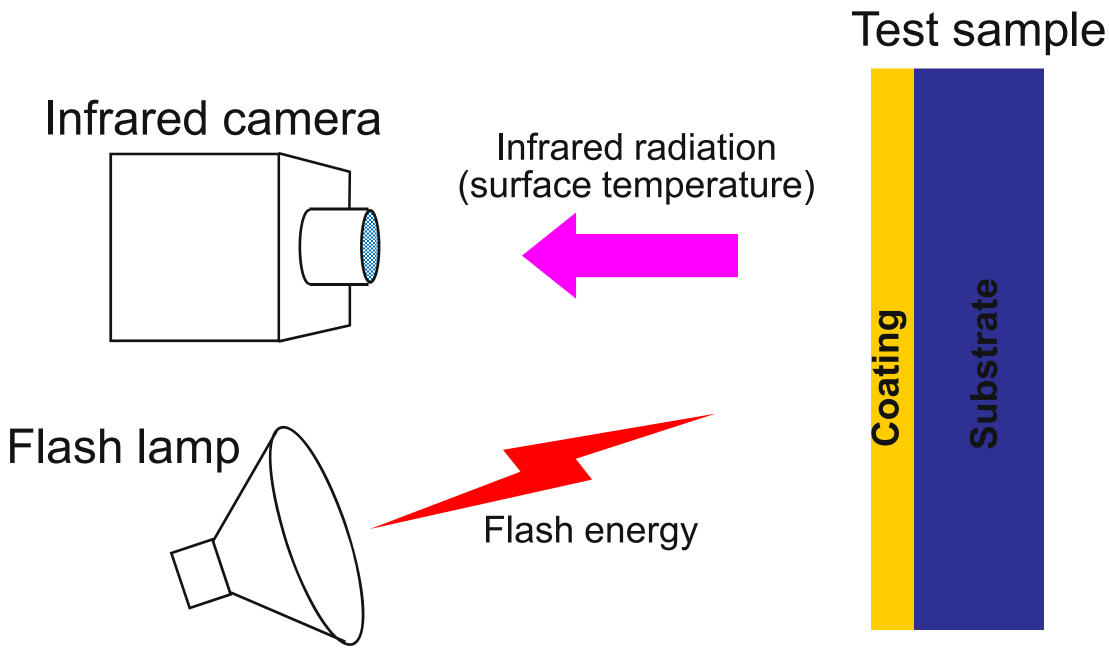
X-ray CT and radiography systems at ANL



CT slice of a 180-mm-dia. ceramic rotor



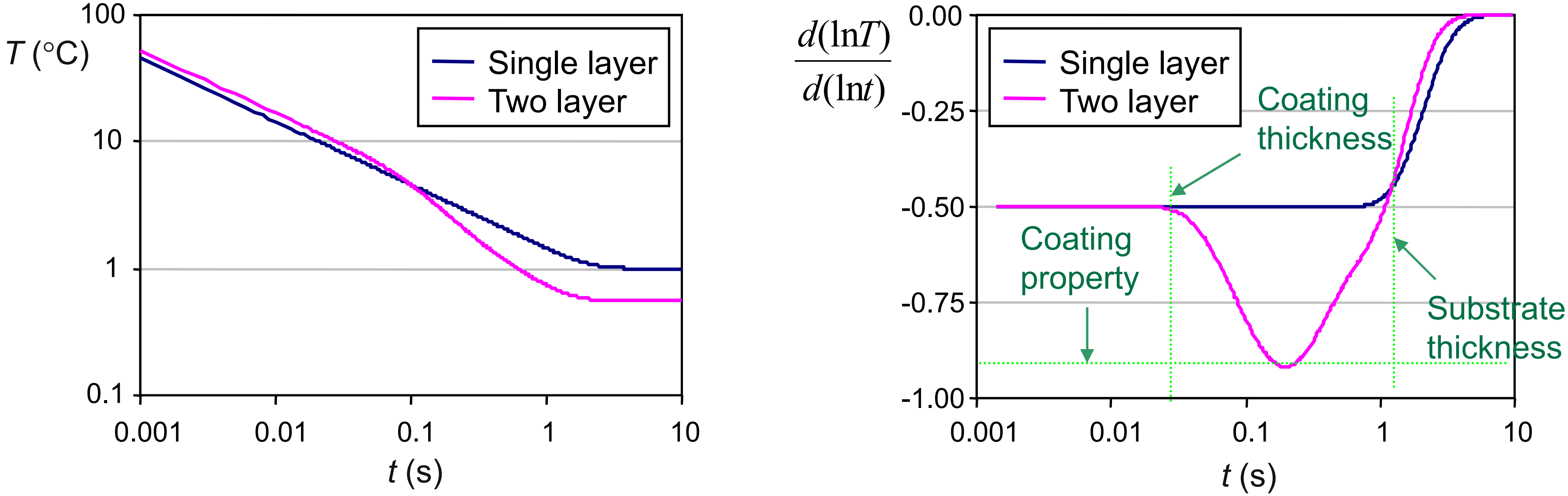
Thermal Imaging Methods for Coatings



- NDE detection principle:
  - An infrared camera continuously monitors sample surface temperature after an instantaneous thermal flash energy is applied on surface
  - Surface temperature data are processed to determine coating parameters
- Advantages:
  - High detection sensitivity due to thermal property disparity in each layer
  - Noncontact, flat or curved surface, fast, and 100% surface inspection

Thermal Imaging for Single- and Two-Layer Materials

Typical thermal imaging data (temperature and its slope) at a surface pixel



- Thermal imaging data, surface temperature and its slope at each surface pixel, are significantly different for single- and multi-layer (eg, coated component) materials
- Characteristics in thermal data allow for direct calculation of coating thickness and thermal properties, as well as substrate thickness
- Thermal imaging methods are being developed for such calculations

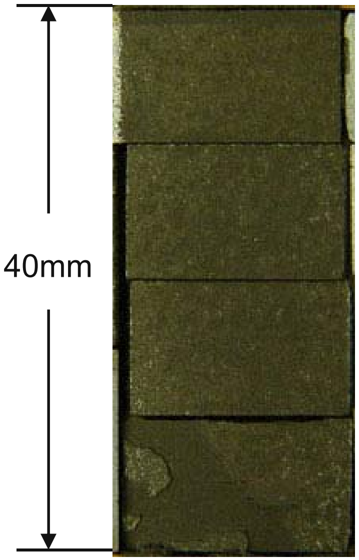
Two Unique Thermal Imaging Methods Are Being Developed at ANL

- Multilayer thermal modeling method
  - Prediction of 2D distributions of coating properties
    - *Thermal conductivity and heat capacity*
    - *Thickness*
  - Determination of coating degradation and delamination

- Thermal tomography method
  - Construction of 3D images of subsurface property/structure
  - NDE detection of coating damages and locations

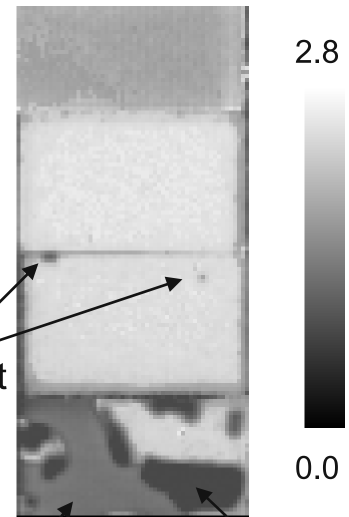
Multilayer Modeling Prediction of TBC Thermal Properties

4 coating samples

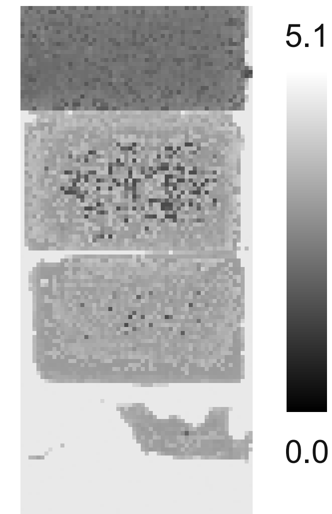


- ❑ coating thickness is 0.2 mm
- ❑ a black paint was applied

Coating conductivity
k (W/m-K)



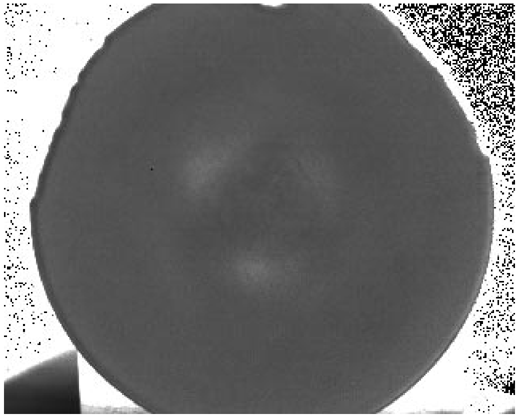
Coating heat capacity
ρC_p (J/cm^3-K)



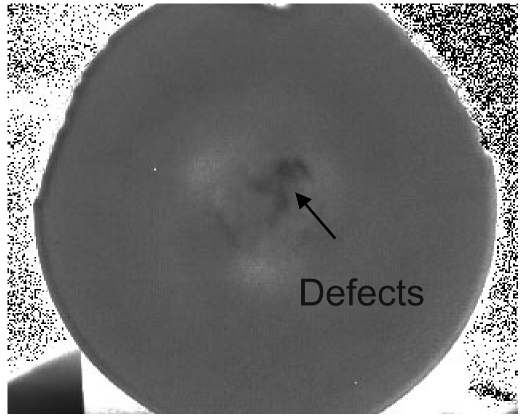
- Coating thermal properties are quantitatively determined
- Sample curtsey of Mr. A. Luz, Imperial College London

Thermal Tomography Imaging of Coating Defects

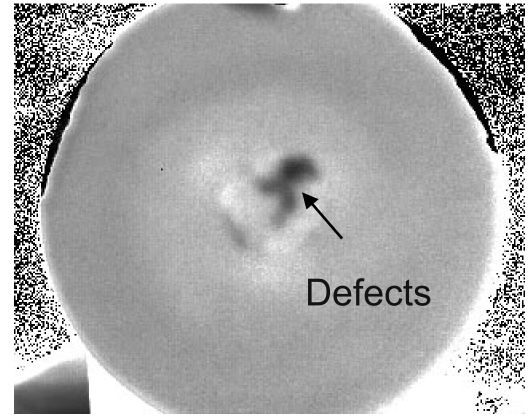
Typical plane thermal tomography images



~0.5mm deep



~0.6mm deep



~1.0mm deep (@interface)

- Defects in coating are clearly detected
  - Defect size/shape - from images
  - Defect "severity" - from grayscale (effusivity)
  - Defect depth - below 0.5 mm (within coating)

Coating thickness ~1.0mm

Future Work

- Continue current development of thermal imaging methods and inspect coating samples and engine components (FY09)
  - Optimize NDE detection sensitivity for coatings of different thicknesses and thermal properties
  - Evaluate coating durability under fatigue/bench test conditions
  - Evaluate coated components after ACERT™ engine tests
- Investigate thermal imaging for inspection of friction-stir-processed surfaces
- Develop NDE methods for inspection of friction-welded joints
- 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 imaging methods for characterizing oxidation-resistant/thermal-barrier coatings for thermal management components. Thermal imaging may also be used to evaluate friction-stir-processed surfaces
- Collaboration with material scientists and engine engineers at Caterpillar and ORNL to develop and apply NDE technologies for critical engine components