

NDE DEVELOPMENT FOR ACERT™ ENGINE COMPONENTS

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Collaborators:

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Overview

Timeline

- Project start: Oct. 2007
- Project end: Sep. 2011
- Percent complete: 80%

Budget

- Total project funding
 - DOE: \$800k
- Funding received in FY10
 - \$200k
- Funding for FY11
 - DOE: \$200k

Collaborators

- Caterpillar Inc.
- ORNL

Barriers

- Barriers addressed:
 - Changing combustion regimes of high-efficiency low-emission engines affecting material properties
 - Long-lead times for material commercialization due partially to material evaluation capability
 - Material weight reduction but with increased strength requirement
- Target:
 - By 2015, develop supporting materials technologies to improve heavy-duty engine efficiency to 50% while meeting emission standards (*VT Multi-Year Program Plan, Dec., 2010*)

Objectives

- Develop rapid, reliable, and repeatable nondestructive evaluation (NDE) methods to support the material enabled high efficiency diesels program (ACERT™ program) to achieve the VT Program Goal of 50% engine efficiency by 2015
- Develop/establish NDE methods and procedures to characterize advanced thermal barrier coatings (TBCs), TiAl casting, friction welded joints, and heat recovery materials etc in:
 - turbocharger components
 - engine exhaust components (with use of TBCs)
 - structural components
 - other components



C-15 ACERT engine
(image provided by Caterpillar)

Milestones

- Develop 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
 - Both thermal imaging and optical scanning methods were used
- Evaluate conventional radiography and synchrotron x-ray CT for NDE characterization of light-weight intermetallic TiAl turbocharger components – Dec. 2010
- Develop/assess synchrotron x-ray CT and ultrasonic NDE technologies for characterization of the quality of friction-welded joints and TiAl castings in diesel engine turbocharger components – Sep. 2011

Approach

- Working with ACERT Program team (Caterpillar and ORNL) to investigate/develop NDE methods applicable to various advanced diesel engine materials/components
 - NDE methods for light-weight intermetallics, ceramics, joints
 - NDE methods for TBCs and turbocharger components

- Current NDE developments are focused on:
 - X-ray NDE inspection of friction welding for turbocharger components
 - *Evaluation of synchrotron and conventional radiography and CT technologies*
 - Synchrotron x-ray CT development for TiAl turbo-wheel castings
 - *Problem addressed: detailed welding and TiAl casting flaws that cannot be detected by other NDE methods*
 - Thermal imaging and optical NDE methods for TBCs
 - *Correlation between NDE methods*
 - *Development of high-resolution thermal imaging method*
 - *Problem addressed: characterization of TBC delamination flaw/damage*

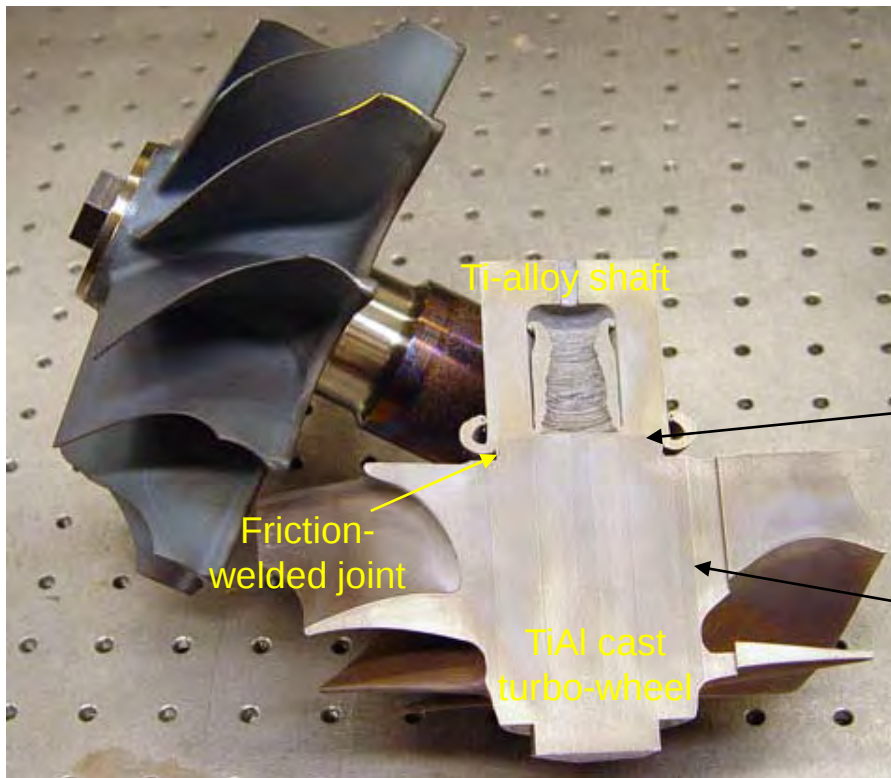


Technical Accomplishments/Progress

- Evaluated conventional and synchrotron x-ray technologies for NDE inspection of friction-welded joints in turbocharger components
 - Conventional NDE technologies have limited sensitivity and resolution
 - High-energy synchrotron CT is suitable for inspection of friction welded joints – first demonstration of synchrotron x-ray CT for industrial parts!
 - Detection sensitivity was established based on correlation of NDE data with destructive inspection result
- Established capability of thermal and optical NDE technologies for high-resolution detection of flaws and delaminations in TBCs
 - Correlation between thermal and optical NDE data was obtained
 - High-resolution thermal imaging method is being developed
- Synchrotron x-ray CT and ultrasonic developments are on-going for inspection of friction-weld joints and TiAl turbo-wheel castings
 - Data process and analysis methods for image enhancement, artifact removal, and detailed flaw extraction from large CT data sets
 - Ultrasonic flaw-detection sensitive and correlation with CT data

NDE for Turbocharger Components

- Turbo-charging improves engine efficiency; lightweight TiAl turbo-wheel improves dynamic response
 - Friction welding for turbochargers has been investigated by Caterpillar
- Application of advanced NDEs improves materials and manufacturing processes and leads to their fast commercialization
- X-ray CT is used for analysis of turbocharger components



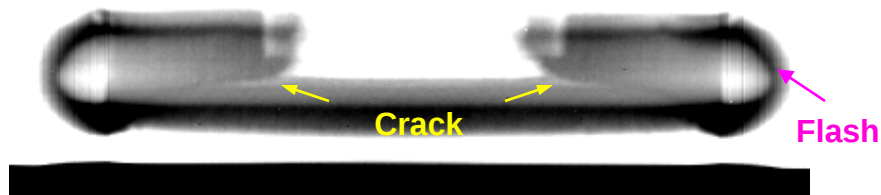
Quality of friction welding is studied

Quality of TiAl turbo-wheel is studied

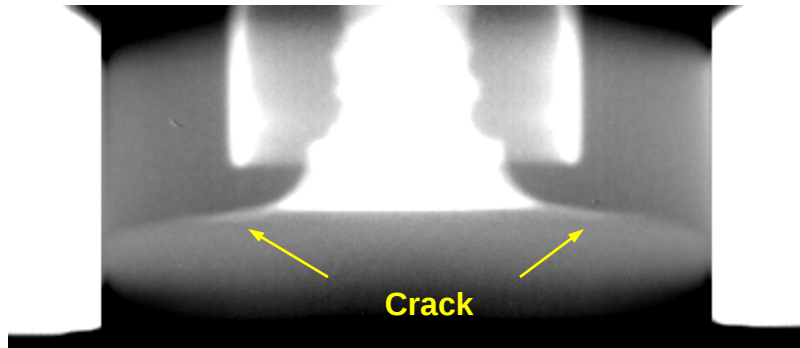
Conventional X-Ray Technologies

Radiography

A weld with flash

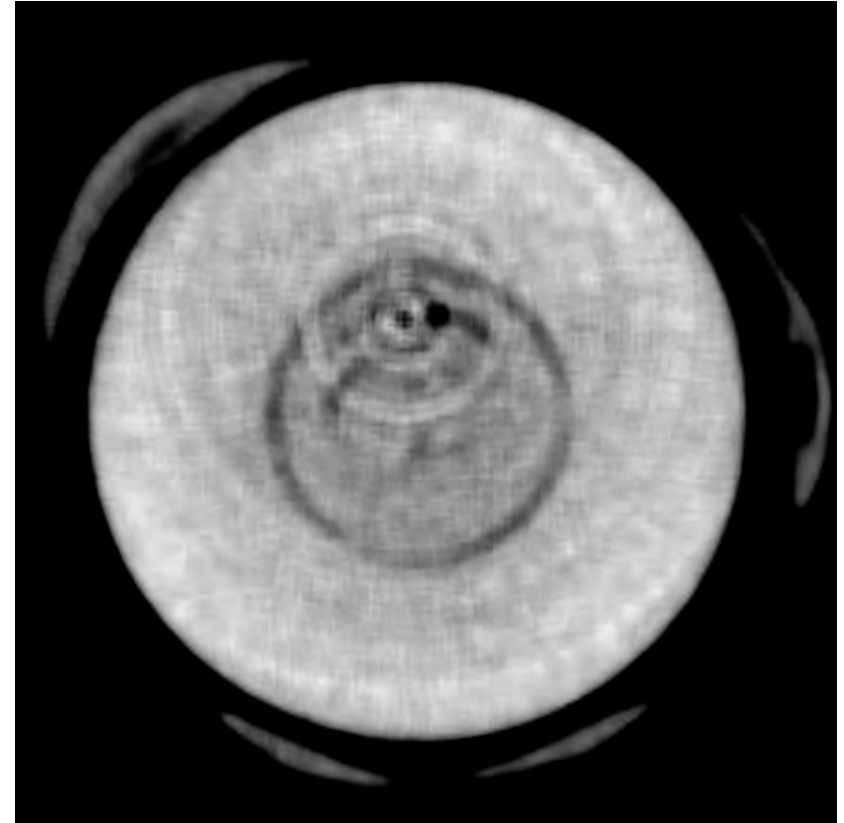


A weld without flash



- Crack resolution is not detailed
 - Pixel size at $\sim 200\mu\text{m}$

Typical CT slice

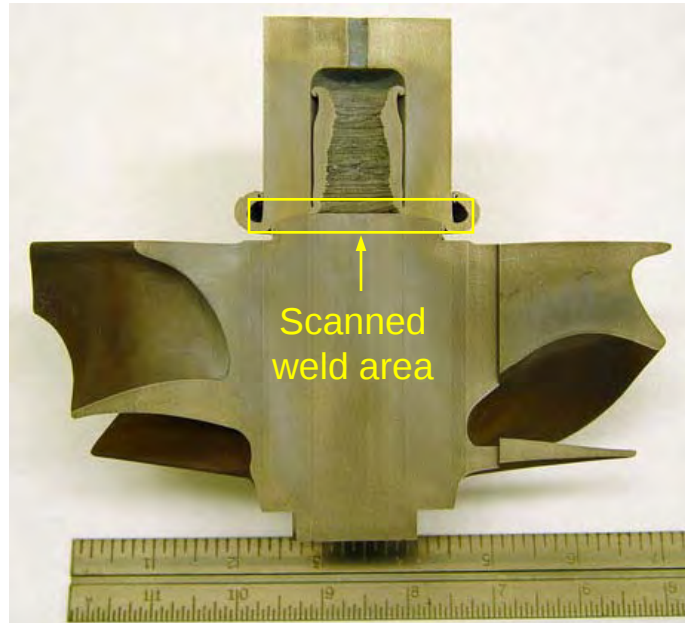


- Insufficient spatial and sensitivity resolution
 - Pixel size at $\sim 80\mu\text{m}$

Conventional x-ray technologies are insufficient for inspection of friction welding

Synchrotron X-Ray CT Technology

Weld calibration sample



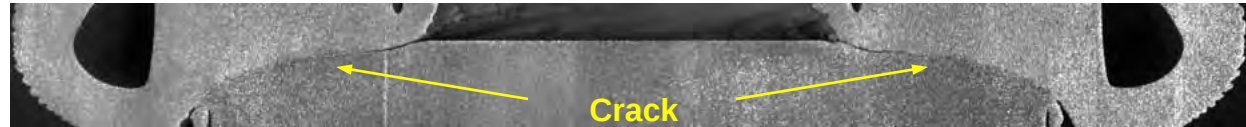
Typical plane CT slices



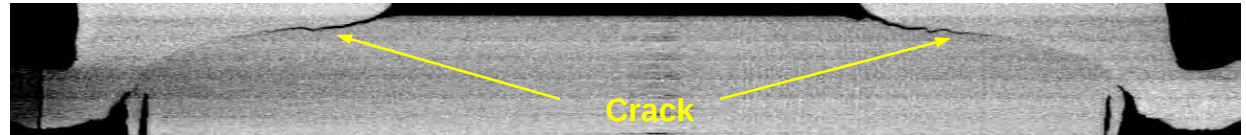
- Tests performed at the Advanced Photon Source (APS) at ANL
- Complex 3D cracks and voids are imaged with high resolution ($\sim 40\mu\text{m}$)
 - Such data help to understand processing issues
 - Such detailed data cannot be obtained by other NDE methods!

Correlation of NDE with Visual Inspection

Visual image
at cut edge

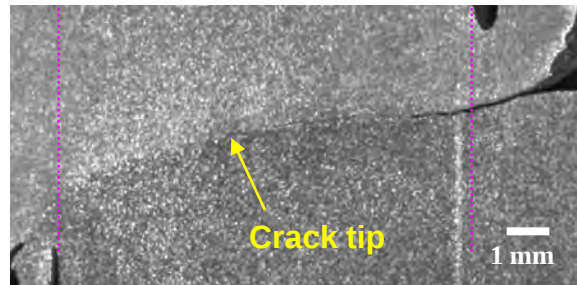


Recomposed CT
slice at cut edge

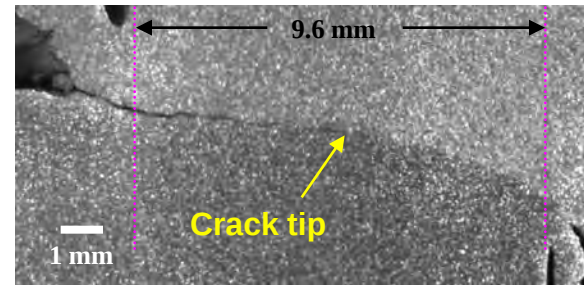


Detailed
comparison

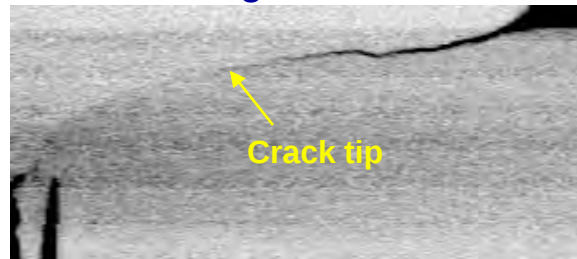
Optical micrograph at left side



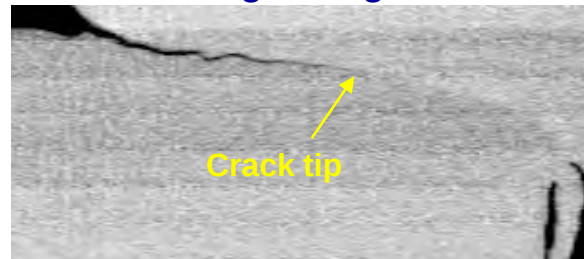
Optical micrograph at right side



CT image at left side



CT image at right side

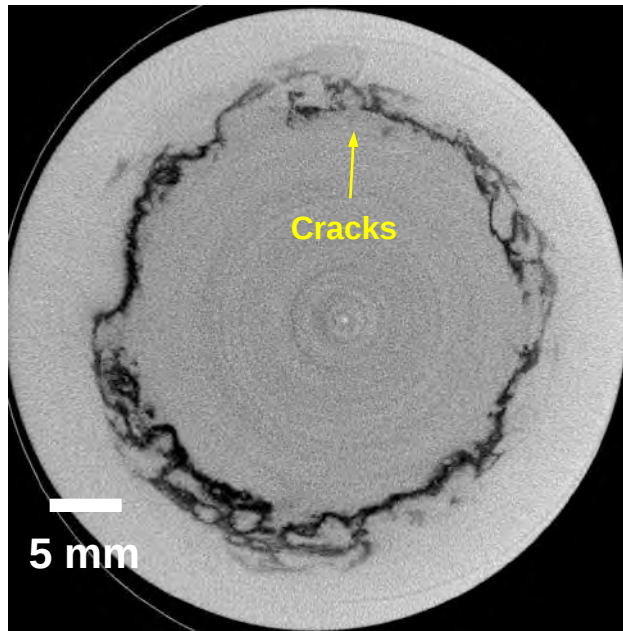


- CT data show better contrast resolution of the crack
- Entire crack, including crack tips, match exactly to the visual inspection image

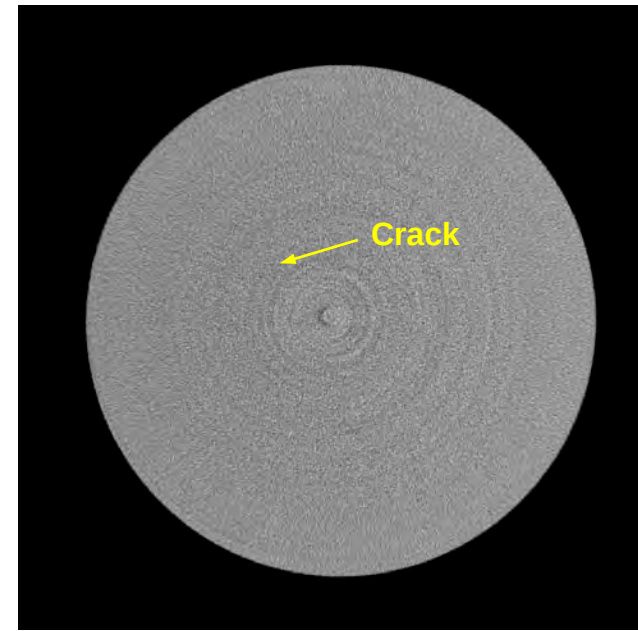
Synchrotron x-ray CT is suitable for inspection of friction welding!

Detection of Welding and TiAl Casting Flaws

CT Slice at welding interface



CT Slice inside TiAl casting



Recomposed Axial CT Slice



- CT data analysis to extract detailed 3D crack information is required
- Detailed characterization of casting cracks requires removal of CT artifacts (ring artifact) – work is on-going

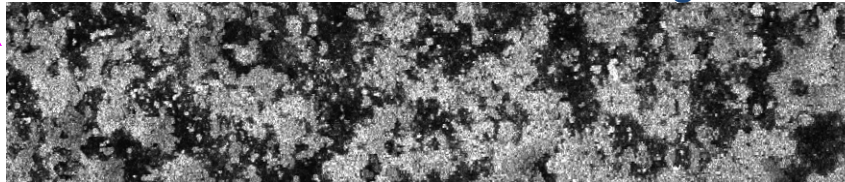
NDE for Thermal Barrier Coating (TBC)

- TBCs applied on engine exhaust components reduce heat loss so improve efficiency; they also replace the use of expensive high-temperature materials
- Delamination is critical flaw/damage in TBC but can be difficult to detect
- NDE developed at ANL: (1) laser backscatter and (2) thermal tomography (TT)
 - Detection principle and capabilities were discussed in previous years' review slides

Optical micrograph of TBC surface



Laser-backscatter scan image

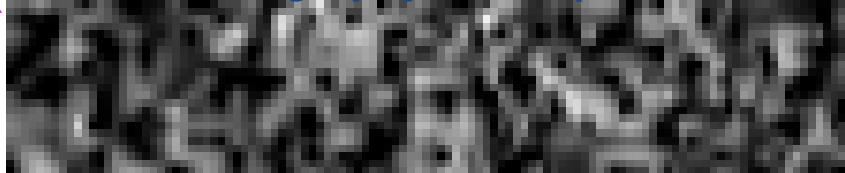


Flaw is brighter

Flaw is darker

Thermal-tomography slices (inside coating)

Slice #1
(on surface)



Slice #5
(within coating)



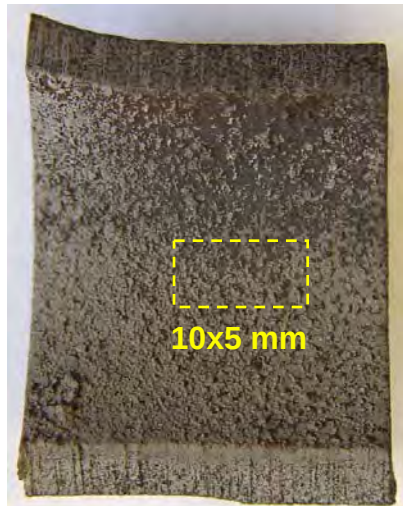
Deeper flaws not
observed on surface

- Correlation is needed to establish detection accuracy of each NDE method

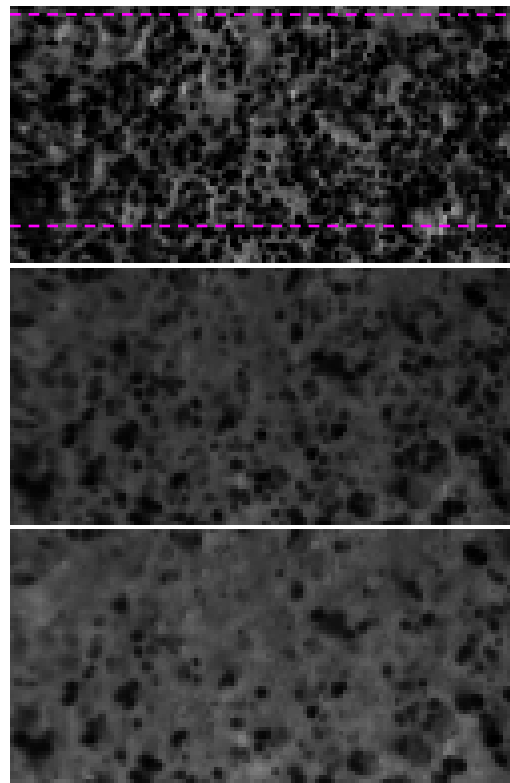
- Good correlation in NDE data and with visual observation
- Thermal NDE may detect deeper flaws not observed on surface

High-Resolution Thermal Tomography (TT) Analysis of TBC Surfaces

Thermal-cycled TBC surface



Plane TT Slices

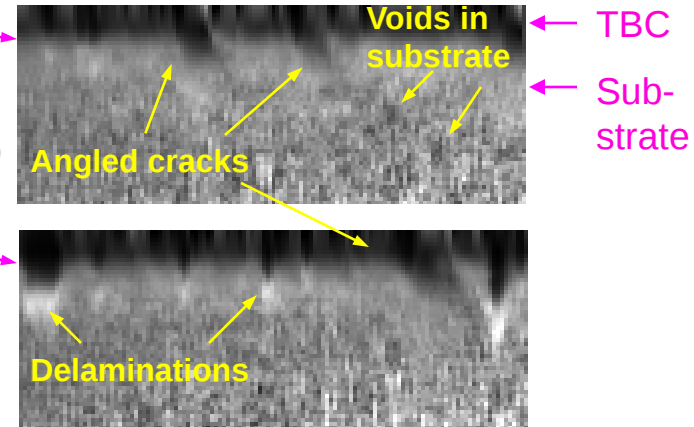


Slice #1
(on surface)

Slice #5

Slice #7
(at TBC-
substrate
interface)

Cross-Section TT Slices



Typical Micrograph

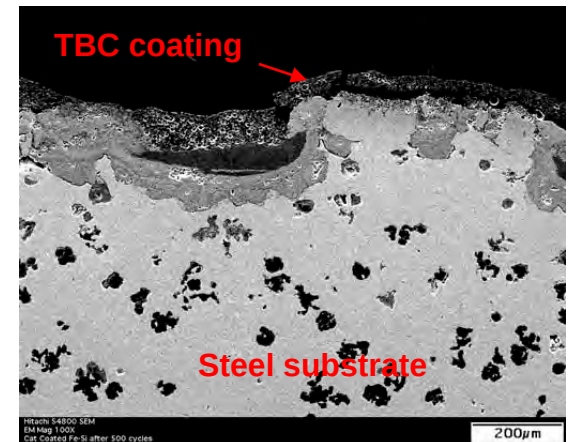


Image from Dr. HT Lin of ORNL

- TBC delaminations and cracks of 0.1mm sizes at various depths are detected
- Voids in Fe substrate are also detected

Collaborations

■ Partners

- Caterpillar (Industry): Collaboration in material processing and 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

- Caterpillar is interested in NDE technologies developed for turbocharger components that can be applied to understand and improve manufacturing process
- Collaborations with researchers at the Center for Thermal Spray Research at Stony Brook University, NASA, and industry to evaluate and validate thermal imaging technologies for characterization of TBCs and other coatings

Future Work

- Continue development of x-ray and ultrasonic NDE methods for inspection of TiAl turbocharger components
 - Detect and analyze friction welding and TiAl casting flaws
 - Develop data processing methods for large 3D CT data sets
 - Develop ultrasonic NDE and establish correlation with CT
- Investigate vibro-thermography NDE technology for detection of fatigue cracks in turbine components
- Investigate NDE methods for power electronic and thermal recovery materials
- Improve detection sensitivity and spatial resolution of thermal imaging method for TBCs

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 synchrotron x-ray CT technology for advanced TiAl turbocharger components
 - Detection sensitivity and resolution for friction welding is established
 - TiAl casting flaws are detected; image enhancement is being developed
- Thermal and optical NDE methods are developed for characterization of oxidation-resistant TBCs for diesel engine exhaust systems
 - NDE data are correlated well
 - Thermal imaging improvement for higher spatial-resolution imaging
- Collaboration with material scientists and engine engineers at Caterpillar and ORNL is essential in developing and applying NDE technologies for critical engine components