Materials for High Pressure Fuel Injection Systems

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** Additional participants are listed at the conclusion of this presentation*

U.S. DEPARTMENT OF ENERGY

Project ID: pmp_02_Blau

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OAK RIDGE National Laboratory

Overview

Timeline

- Project start date: July 2008
- Project end date: September 2011
- Percent complete: 15%

Budget

- Total project funding (CRADA)
  - ORNL / Caterpillar Corp
- FY08: $ 225K / $ 225K*
- FY09: $ 225K / $ 225K*
- FY10: $ 225K / $ 225K*

* In-kind

Barriers

Barriers addressed:

- Improve engine system fuel efficiency for Class 7-8 trucks by 20% by 2010.
- Fuel injection design pressures continue to rise to boost engine efficiency. Nozzle tip materials surrounding spray holes must resist high-pressure fatigue effects.

Partners

- Caterpillar Corp. (CRADA)
- Project lead: ORNL jointly with Caterpillar Inc.

Barriers (continued)

- The injector nozzle, with its pattern of 50-300 μm diameter holes, is the key to precise fuel metering, combustion characteristics, and emission control. Injector design pressures have risen steadily in recent years.
- Challenge 1: Holes must maintain dimensional tolerances and flow characteristics for tens of millions of pressure cycles.
- Challenge 2: Nozzle materials must resist changes in shape, and allow holes to remain clear and open despite increasingly high injection pressures.
- Challenge 3: What are the effects of residual stress state, hole bore characteristics, and metallurgy on the high-cycle fatigue response of nozzle tips?
- Challenge 4: Will current injector tip materials withstand the new design requirements, and if not, what alternative materials may be suitable?

Project Objectives

- To critically evaluate current and future material choices for high-pressure fuel injector nozzles intended for energy-efficient, low emissions diesel engines.
- To provide metallurgical analysis, fatigue test data, hole metrology information, residual stress measurements, and guidance on selection of alternative high-performance alloys to designers of advanced, high-pressure diesel engine fuel injector systems.

Milestones for FY 2009

Month / Year	Milestone
Jan / 2009	**Hole metrology**: Develop methods to measure the roughness and surface features of the interior of spray holes, especially features that could affect fatigue crack initiation and fuel mixture flow.
Mar / 2009	**Evaluate ability for x-rays and neutron methods to measure residual stresses in injector tips**: Using facilities at ORNL, as well as other national laboratories, establish the feasibility of mapping residual stresses in injector tips near spray holes.
Jun / 2009	**Design and develop fatigue-testing method(s) to simulate high-pressure tip loading**: Develop fatigue tests that simulate the expected stress states, and which can be applied to investigate spray hole characteristics and alternative nozzle material choices.
Sep / 2009	**Determine the relative fatigue performance of candidate materials for high-pressure tips:** Use fatigue test design to analyze current and new materials and processes for tip geometry.

Approach

CAT HEUI diesel fuel injector

Characterization of Current Nozzle Materials and Design Features **

Identification of Candidate Advanced Materials for High Pressure Nozzles **

Spray Hole Bore Characterization *

Sample lots of advanced alloys for testing****

Metallurgical Characterization **

Residual Stress Measurements *

Fatigue Testing With and Without Simulated Spray Holes **

Fuel Injection Component Modeling and Improved Manufacturing Processes ***

Evaluation of Hole-Making Methods, if necessary ****

*** ORNL**

**** ORNL and CAT**

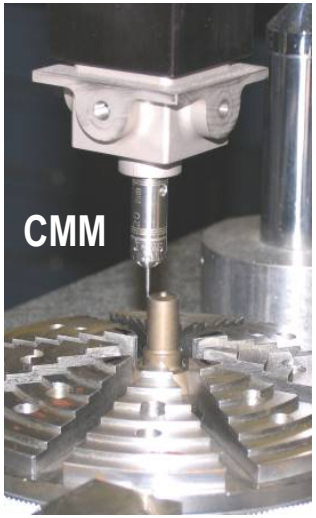
***** CAT**

****** CAT and suppliers**

Technical Progress and Results
(Specimens and Background Data)

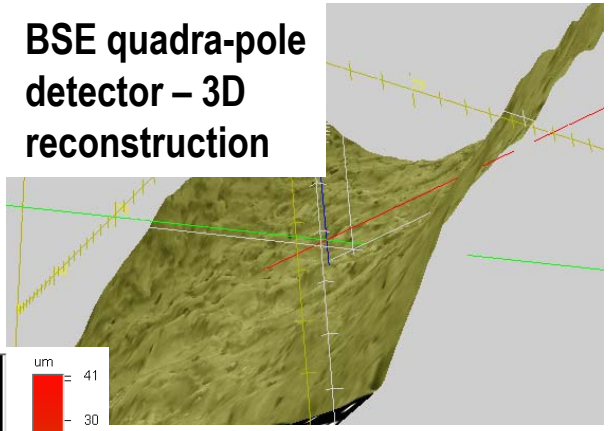
- Caterpillar provided materials and information on:
  - Current generation of fuel injector materials,
  - Characterization and metallographic studies of current materials
  - Information on manufacturing methods

Technical Progress and Results
(Hole Characterization)

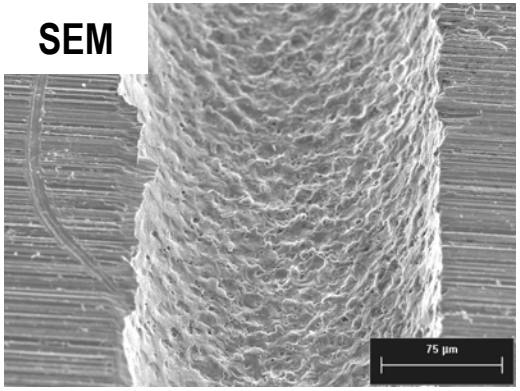


- Application of multiple techniques to characterize tips and holes
  - Develop specialized mounting techniques
  - Coordinate measurement (CMM)
  - Optical / scanning electron microscopy
  - BSE quadrapole 3D reconstruction
  - Optical interferometric profiling in 3D
  - X-ray micro tomography

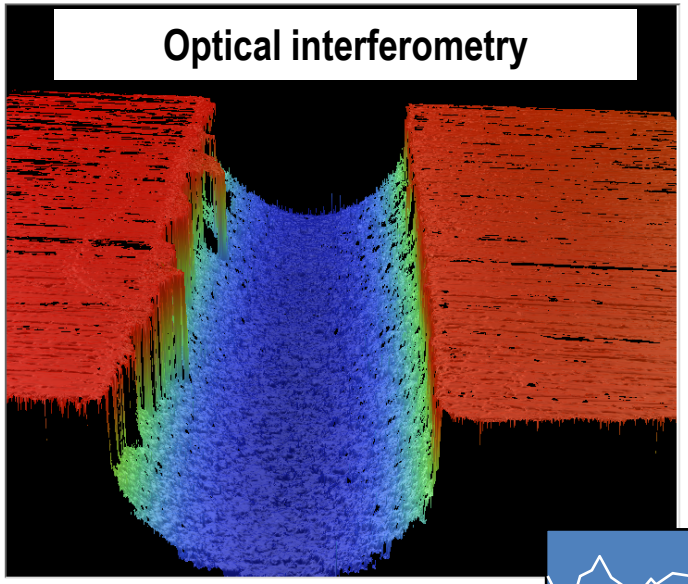
BSE quadra-pole detector – 3D reconstruction

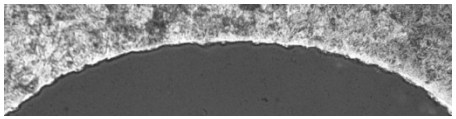


SEM

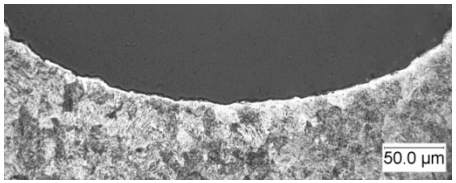


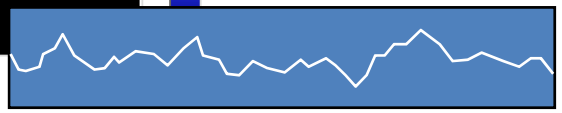
Optical interferometry





Etched microstructure





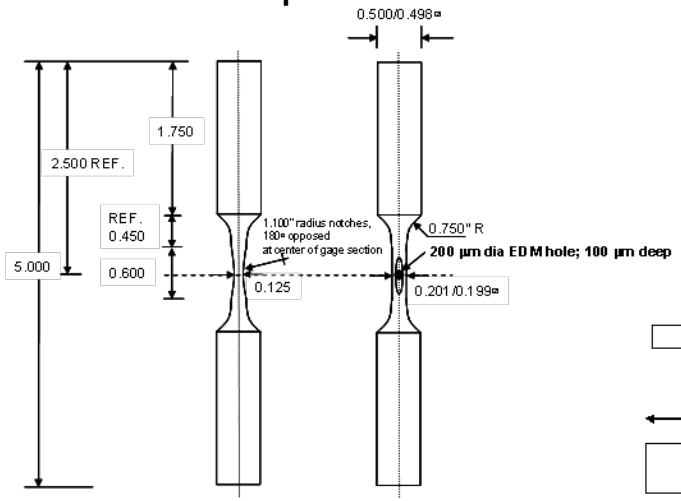
Hole bore roughness

Technical Progress and Results
(Fatigue Testing 1/2)

Challenge : To introduce cyclic stress fields similar to those generated at the tip of a fuel injector during operation.

A Dual Approach

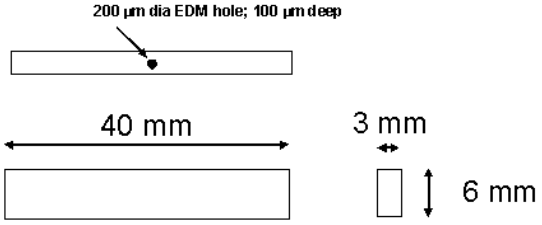
Stress-life
Smooth specimens



Dimensions are in inches except where mentioned

Fracture Mechanics
EDM hole specimens

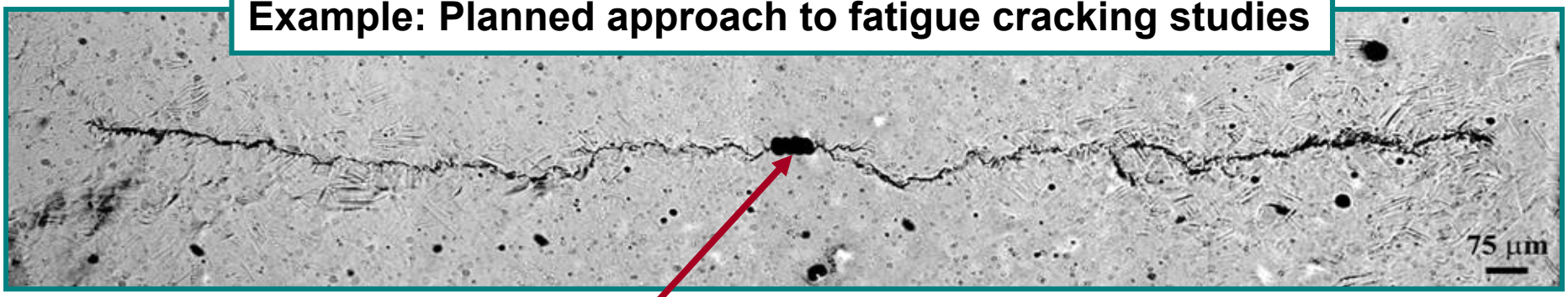
X-ray residual stress to be included in fatigue specimen characterization



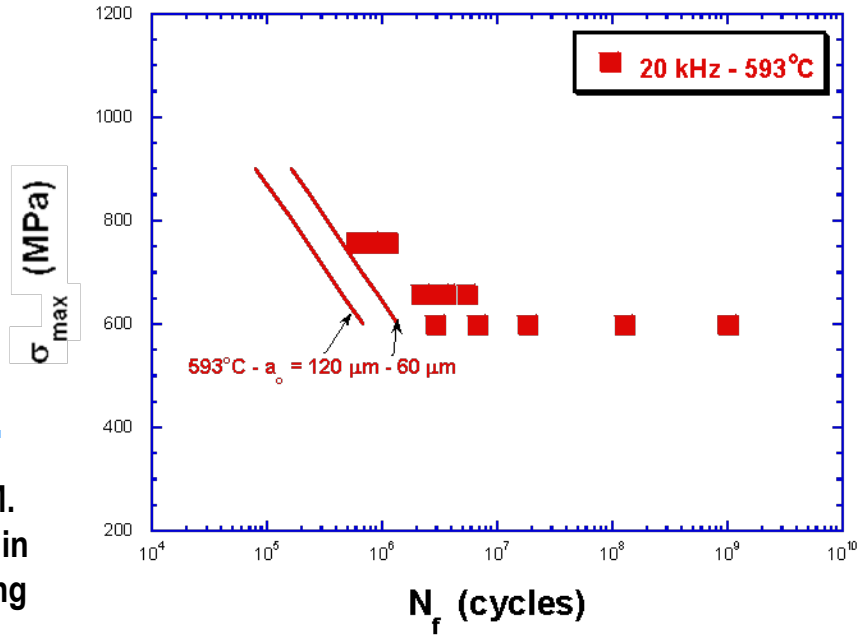
- Bending and uniaxial test geometry
- Fracture mechanics specimens have EDM holes similar to fuel injector tips
- Smooth specimens without any additional stress concentrations to determine the weakest link in the microstructure

Technical Progress and Results
(Fatigue Testing 2/2)

Example: Planned approach to fatigue cracking studies



- Fatigue crack growth from a ~100 μm notch in Rene' 88DT Ni-base superalloy.*
- Conditions of interest: high frequency, long lifetimes.
- Prediction of the worst case behavior is based on small crack propagation rates at 20 kHz.



*** Reference: A. Shyam, J. E. Allison, C. J. Szczepanski, T. M. Pollock and J. W. Jones (2007) "Small fatigue crack growth in metallic materials: A model and its application to engineering alloys", *Acta Materialia*, 55 (19), pp. 6606-6616.**

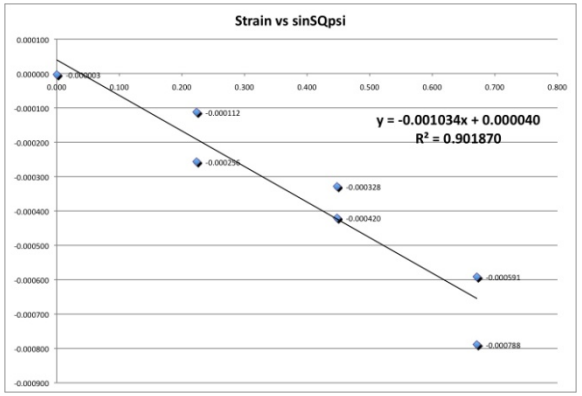
Technical Progress and Results
(Residual Stress Measurements 1/2)

Challenge: To measure residual stresses on the surface and through thickness due to processing and their changes due to operation (temperature and fatigue)

Approach: Test the feasibility and achievable spatial dimensions using DOE X-ray and neutron diffraction stress mapping facilities

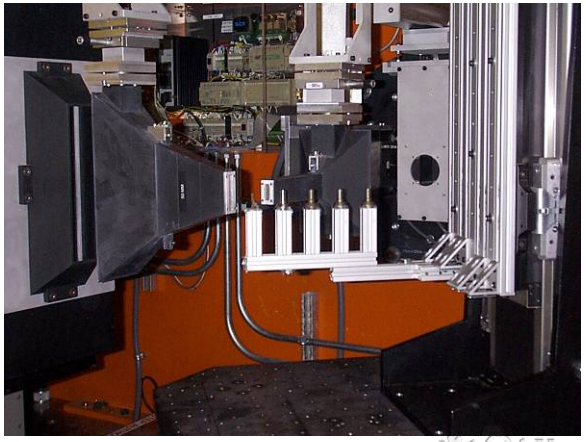
- Surface stresses in smooth bend test specimens by laboratory X-ray diffraction
- Surface stresses in nozzles by synchrotron X-ray diffraction
- Through thickness residual stresses by neutron diffraction mapping at HFIR

Lab XRD on bend bar



Synchrotron XRD at NSLS

Neutron stress mapping at HFIR



Technical Progress and Results
(Residual Stress Measurements 2/2)

Technique	Facility	Samples	Comments/findings
Laboratory XRD	ORNL-PTS goniometer	Bend rods	Compressive axial surface stresses resulting from carburizing heat treatment
Synchrotron XRD (low energy x-ray)	NSLS – X14A	4 nozzles	Compressive stresses at surface Beam size limited to 1x2 mm
Synchrotron XRD (high energy x-ray)	APS, ALS, Stanford (tbd)	nozzles	Goals are depth mapping gauge volume below 0.3x0.3x0.3 mm (To be scheduled)
Neutron diffraction	HFIR-NRSF2	4 nozzles	Measured d-spacing through barrel wall. Gauge volume limited to 0.5x0.5x5 mm. Unable to determine stress free d-zero needed to calculate strains. Possible gauge volume not small enough.

Future Work

- Continue to improve methods to measure the geometrical and metallurgical characteristics of spray holes
- Continue X-ray residual stress studies
  - Assess APS and ALS capabilities to measure stresses with <0.2 mm x-ray spot size
- Continue studies of X-ray microbeam tomography – a non destructive spray hole characterization
  - Trial at NSLS-X3B beam line -- 30 keV was not sufficiently penetrating
  - Phoenix X-ray Systems (up to 120 keV) – assessment March 19, 2009
  - ALS synchrotron (up to 70 keV)– sent finished nozzle for assessment measurements
- Complete the development of a fatigue test method to study the effects of fine holes in advanced alloys under stress states similar to those in fuel injectors.
- Investigate the process of hole-making on the internal features of the holes, as they affect fatigue crack initiation and propagation.

The CRADA Team
Acknowledgments

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  - **Peter Blau (co-principal investigator, hole imaging and metrology)**
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- **CATERPILLAR:**
  - **Mike Pollard (co-principal investigator, materials, fatigue analysis)**
  - **Ally Stahl (metallurgy and alloy characterization).**
  - **Jeff Jensen (supervision and coordination within Caterpillar)**

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Summary

This Cooperative Research and Development Agreement (CRADA) is aimed at meeting the need for materials to withstand demanding stress conditions in high-pressure diesel engine fuel injectors. The following has been accomplished since the start of work in July 2008:

- Caterpillar provided specimen materials and information on current injectors
- Alternative methods have been explored to quantify the size, internal features, bore roughness, and microstructures near fuel injector spray holes. Hole bore roughness measurements have been obtained using both multi-detector 3D construction in the SEM and light-optical interferometric methods.
- X-ray and neutron-based methods have been evaluated to determine the feasibility of mapping residual stresses in the vicinity of the nozzle tip holes. Despite several inherent limitations of some techniques, initial results indicate minimal residual stresses in the current alloys.
- A dual-approach fatigue testing plan, coupled with residual stress studies, has been developed to investigate the effects of holes on fatigue crack initiation and propagation in current and future nozzle tip materials.