Materials for High Pressure Fuel Injection Systems

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OAK RIDGE National Laboratory

Overview

Timeline

- Project start date: July 2008
- Project end date: September 2011
- Percent complete: 60%

Budget

FY	ORNL Planned	ORNL Rec'd	CAT Planned
2008	225K	225K	225K*
2009	225K	225K	225K*
2010	225K	152K	225K*
2011	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. Materials surrounding nozzle spray holes must resist high-pressure fatigue.

Partners

- Project lead: ORNL, jointly with Caterpillar Inc.
- CARTECH (collaborating)

Relevance

- Diesel engine designers continue to optimize engine designs to meet fuel efficiency challenges and government emissions requirements.
- A fuel injector nozzle, with its pattern of fine spray holes, is key for precise fuel metering to control combustion characteristics and reduce emissions.
- Injector design pressures have risen steadily in recent years and that has generated four key challenges for material selection:
  - 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 evaluate spray hole microstructures, nozzle residual stress states, and fatigue properties of current and future materials for high-pressure fuel injector nozzles for energy-efficient, low emissions diesel engines.
- To apply advanced instruments and materials analysis tools to establish links between the microstructure of alloys for high-pressure fuel injectors and their resistance to fatigue crack initiation and growth under both ambient and fuel laden environments.

Milestones for FY ‘09 and ’10 (Slide 1 of 2)

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:** *(Delayed until July 2010, due to the non-availability of specimen materials).*

Milestones for FY '09 and '10 (Slide 2 of 2)

Month / Year	Milestone
Jan / 2010	☑ **Complete installing a tele-microscope to image fatigue cracks in situ**: Install an optical tele-microscope to enable the documentation of fatigue cracks propagating from the edges of a defect in a servo-hydraulic testing machine.
Feb / 2010	☑ **Characterize the fine structure of spray hole walls using transmission electron microscopy**: Using facilities at ORNL, as well as other national laboratories, establish the feasibility of mapping residual stresses in injector tips near spray holes.
Sep / 2010	**Determine and report the fracture characteristics of current and candidate alloys.** Supplement fatigue test data with an assessment of the fracture toughness. Then complete an analysis of alloy sensitivity to crack propagation.

A Three-Pronged Approach

CAT® HEUI diesel fuel injector

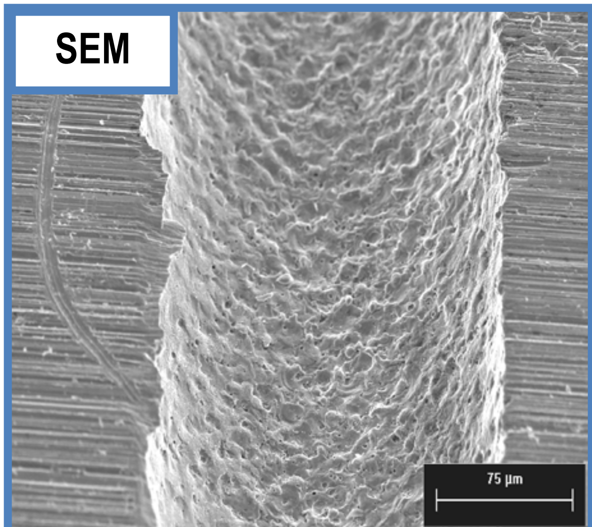
1) Characterize the **dimensions and microstructures** of alloys in the vicinity of spray holes, with special attention to fatigue crack initiation sites.

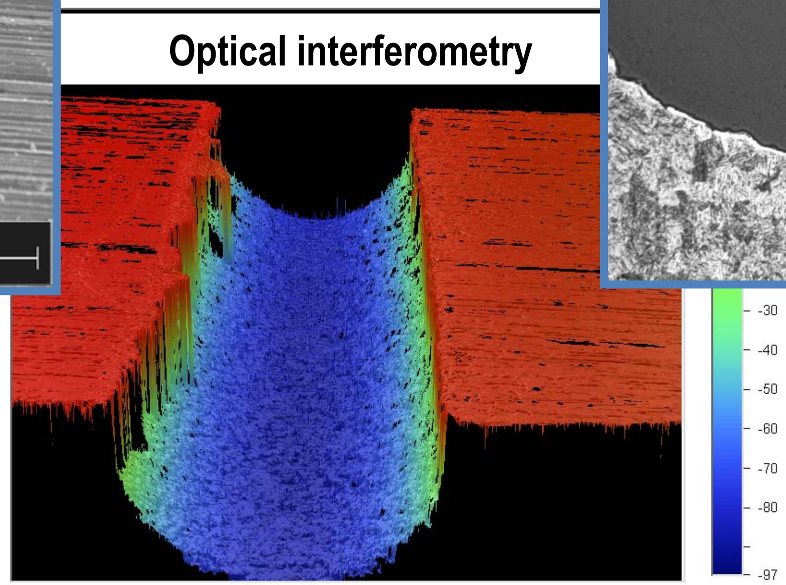
2) Characterize the **residual stress state** of the current alloys in the nozzle tip to determine if that may influence fatigue crack initiation or retardation.

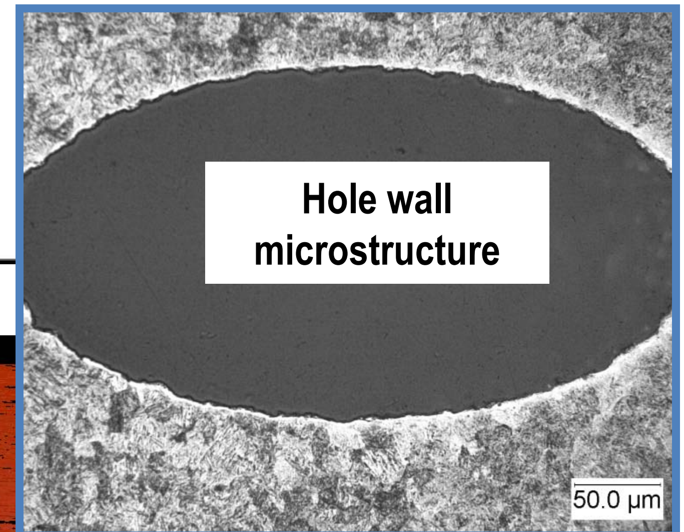
3) Using laboratory tests, investigate the **fatigue behavior of current and advanced alloys for fuel injector tips**, as affected by the presence of fine holes and fuel environments.

Technical Accomplishments and Progress: (1) Microstructural studies and measurements

- Used a variety of complementary methods to characterize the dimensions, bore roughness, microstructures, and fine structure of materials in and surrounding spray holes

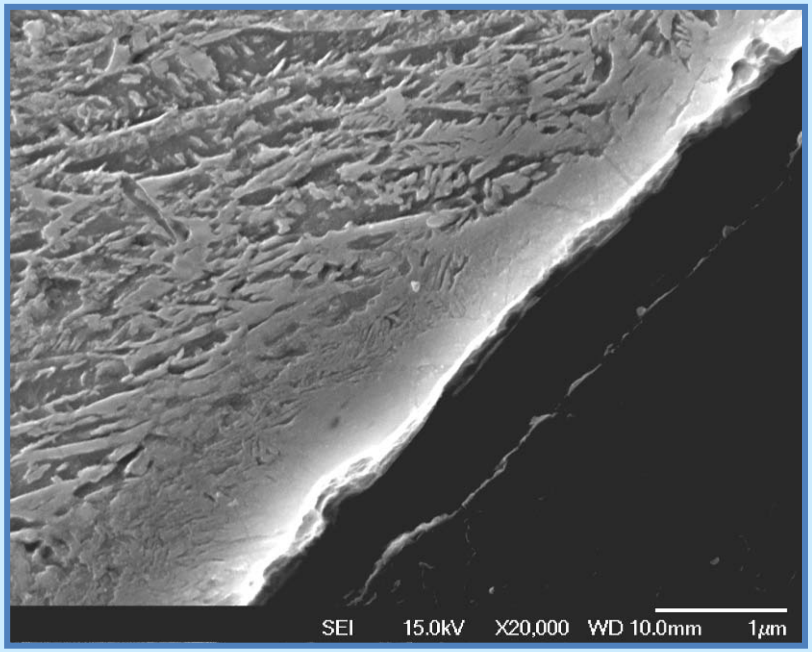




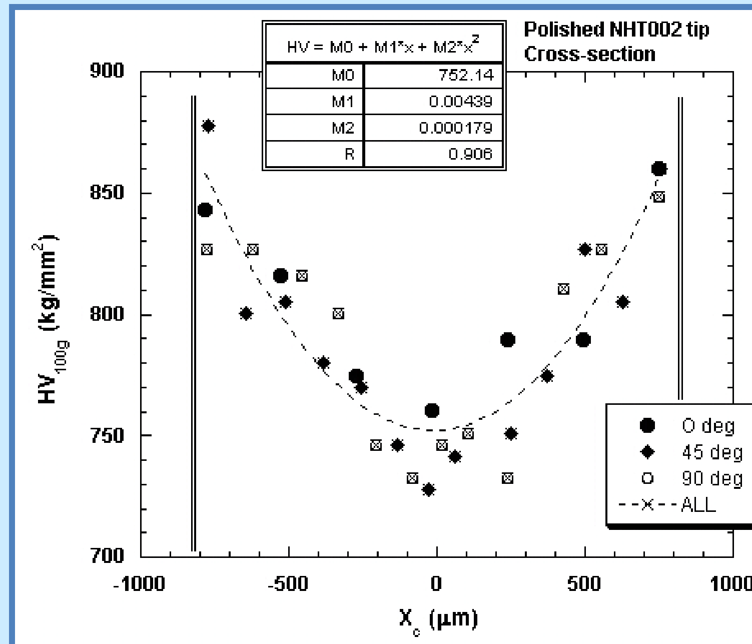


Technical Accomplishments and Progress: (1) Microstructural studies and measurements

Cross-sections and hardness profiles in nozzle tip (sack)



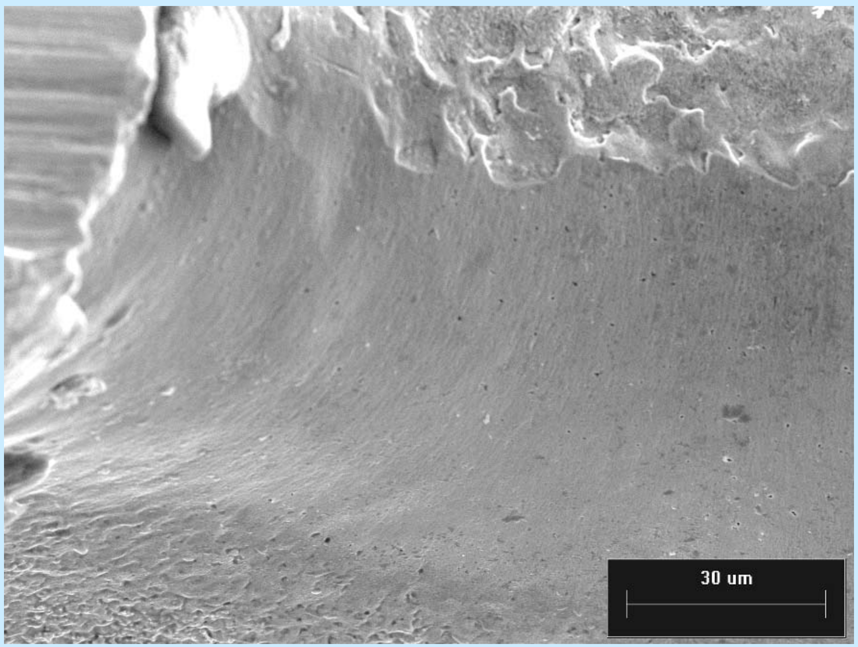
SEM of a heavily-etched hole wall



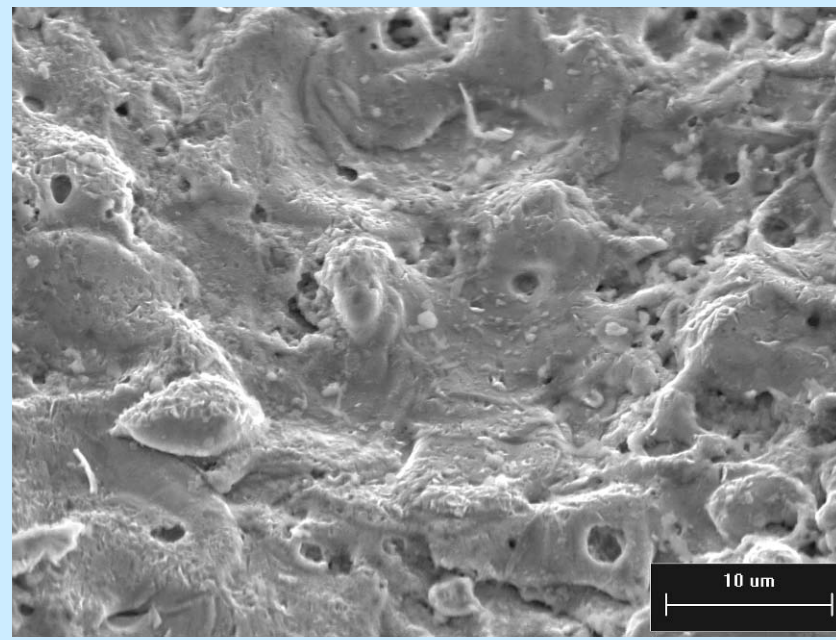
Properties varied through the wall thickness

Technical Accomplishments and Progress:
(1) Microstructural studies and measurements

Hole wall features could originate microcracks under repeated high-pressure pulsation



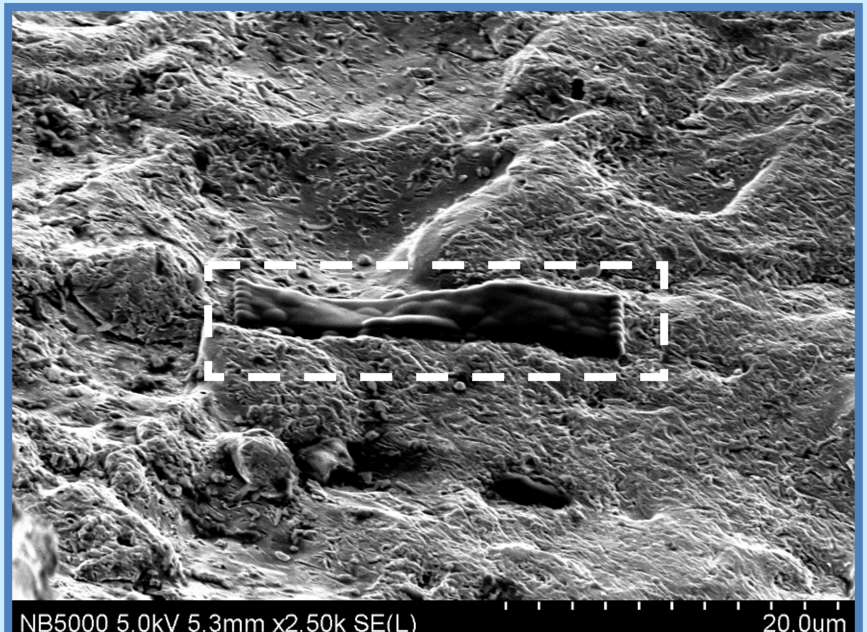
Spray hole inlet region (smooth)



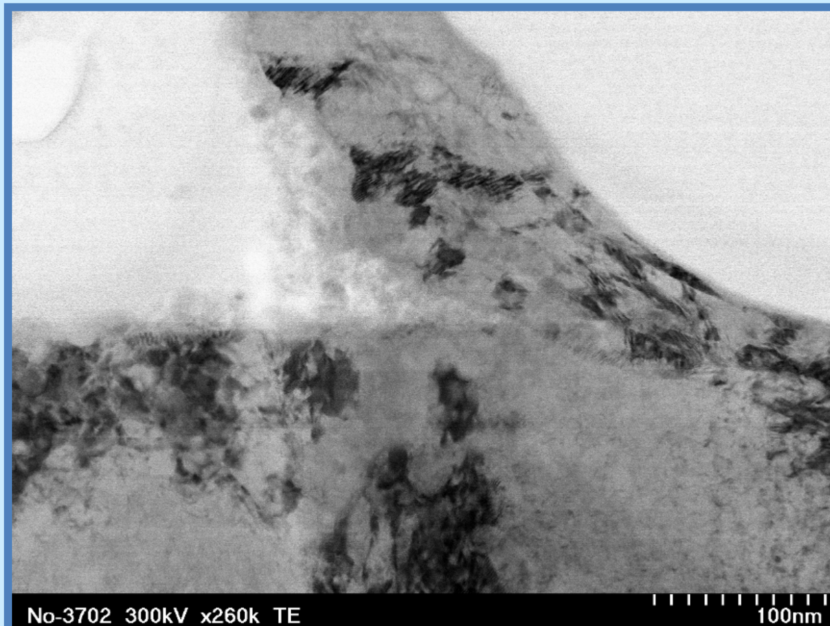
Rougher area of a hole wall showing splats and pores

Technical Accomplishments and Progress: (1) Microstructural studies and measurements

A Focused Ion Beam (FIB) was used to cut a slice from the recast zone for Transmission Electron Microscopy studies (Coffey/Howe)



FIB'ing a slice from the hole wall after capping it with a metallic film



Cross-section of the slice showing fine structure in the re-cast zone

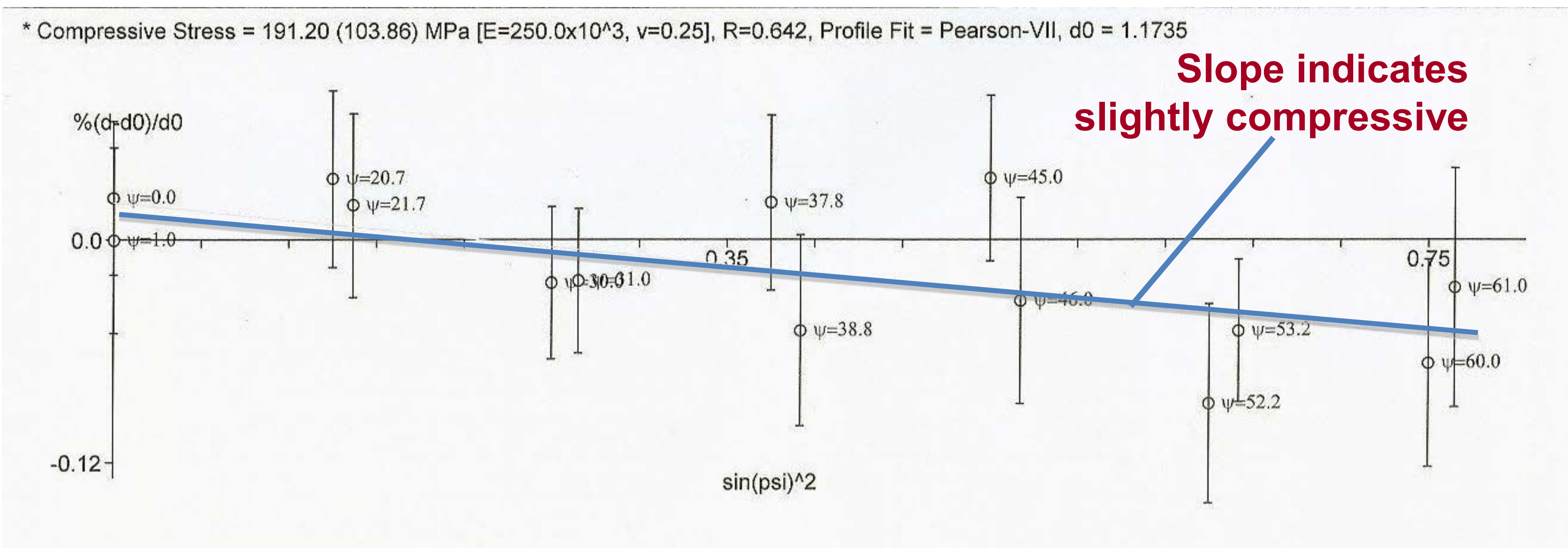
Technical Accomplishments and Progress:
(2) Residual stress studies of nozzles

Three DOE X-ray and neutron diffraction stress mapping facilities were used in an attempt to establish the feasibility of achieving the spatial dimensions required to characterize materials in fuel injector nozzles.

Technique	Facility	Comments/findings
Laboratory XRD	(ORNL / HTML) PTS goniometer	Compressive axial surface stresses resulting from carburizing treatment
Synchrotron XRD (low energy x-ray)	(BNL) NSLS – X14A	Compressive stresses at surface Beam size limited to 1x2 mm
Neutron diffraction	(ORNL / HTML) HFIR-NRSF2	Measured d-spacing through barrel wall. Gauge volume limited the ability to determine stress free d-zero needed to calculate strains.

Technical Accomplishments and Progress:
(2) Residual stress studies of nozzles

Example: Results from Brookhaven National Lab (National Synchrotron Light Source) indicated a slight compressive axial compressive stress in a nozzle tip.



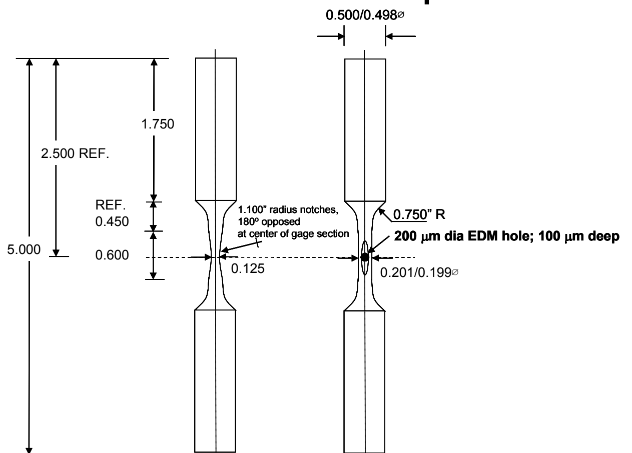
- A straight line fit should exist if there were no shear stresses at the surface
- Error bars are significant, partially due to the heat-treated condition's leading to broad diffraction peaks

Technical Accomplishments and Progress:
(3) Fatigue studies of alloys

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

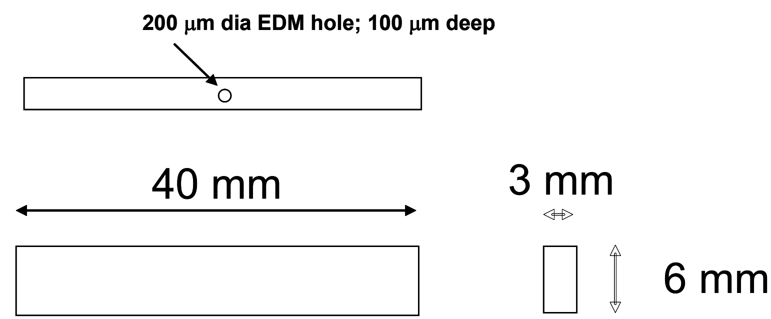
A DUAL APPROACH

Stress-life - Smooth specimens



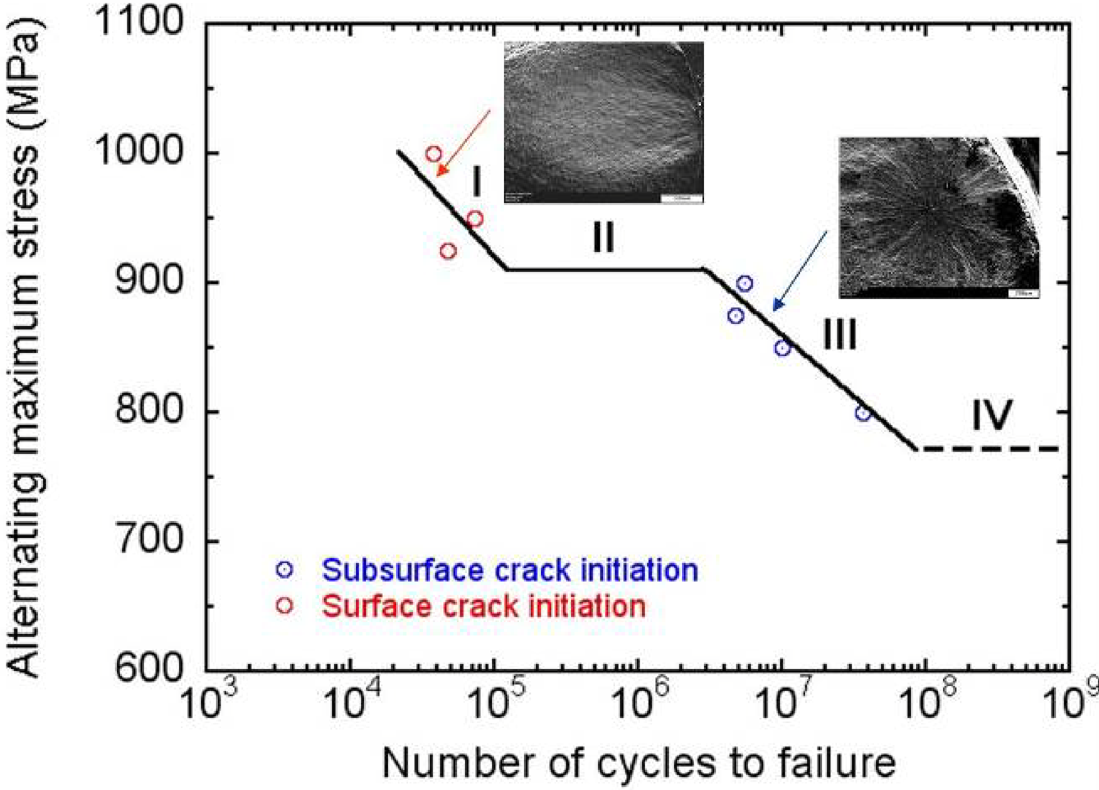
Dimensions are in inches except where mentioned

Fracture Mechanics - Hole specimens



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

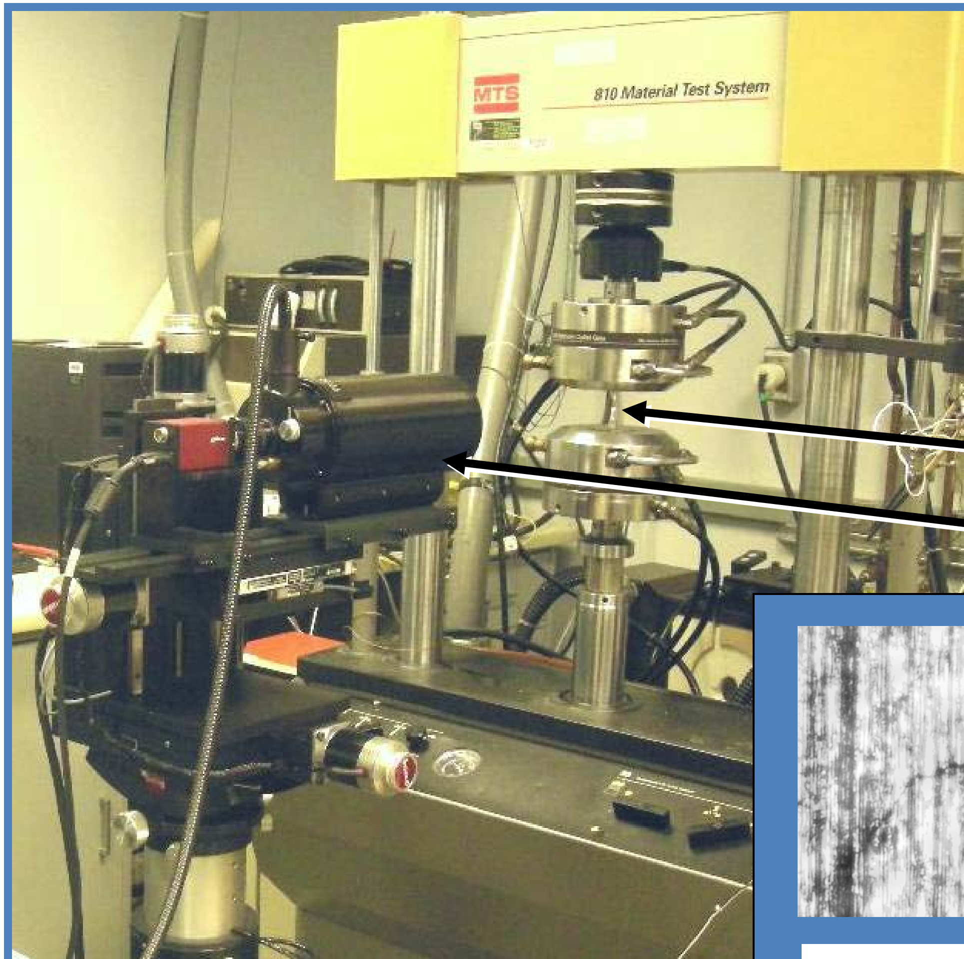
Technical Accomplishments and Progress:
(3) Fatigue studies of the current alloy



Two different modes of crack initiation were observed, depending on the stress level.

- "Short life" failures have surface crack initiation > 900 MPa
- "Long life" failures have subsurface crack initiation at σ_{max} < 900 MPa

Technical Accomplishments and Progress:
(3) Fatigue crack initiation near holes



A new Questar™ 'tele-microscopy' system was purchased and installed on a fatigue test frame to observe and measure crack initiation and growth near holes in the alloy steel.

Fatigue specimen

Tele-microscope

Example: laser-machined notch

Summary of Annual Progress

This Cooperative Research and Development Agreement (CRADA) is aimed at enabling materials to withstand the demanding stress conditions of high-pressure diesel engine fuel injectors. The following highlights were accomplished since the start of work:

- (FY 08/09) Complementary methods were used to quantify the size, internal features, bore roughness, and microstructures at fuel injector spray holes.
- (FY 09) X-ray and neutron-based methods were used to investigate residual stresses in fuel injector nozzles. Results suggest that residual stresses in the nozzles are not a significant issue, and further work was suspended.
- (FY 08/09/10) A fatigue test plan was developed and used to study the effects of holes on fatigue crack initiation and propagation in current and future nozzle materials. A dual-mode crack initiation was observed.
- (FY 09/10) The microstructures at the walls of spray holes were studied by a combination of techniques, including focused ion beam methods and transmission electron microscopy.

Collaboration and Coordination with Other Institutions

- **ORNL and Caterpillar Inc.** are partners in a multi-year Cooperative Research and Development (CRADA)

  CAT provides test materials, shares fatigue test data, and supplies information on both material durability criteria and fuel injector operating conditions.

- Collaboration is under way with **Carpenter Technology Corporation** (CARTECH), a supplier of high-performance specialty steel products, headquartered in Reading, Pennsylvania.

  > CARTECH is providing advanced alloys and data for evaluation as an alternative to the current nozzle material

The Project Team
Acknowledgments

- **ORNL**
  - **Peter Blau (co-principal investigator, metallurgical studies, test methods)**
  - **Cam Hubbard (residual stress measurement and analysis)**
  - **Amit Shyam (fatigue and fracture testing and modeling)**
  - **Randy Parten (coordinate measurement and precision grinding)**
  - **Brian Jolly (hole bore roughness measurements)**
  - **Dorothy Coffey (FIB specimen preparation)**
  - **Jane Howe (TEM studies)**
- **CATERPILLAR:**
  - **Mike Pollard (co-principal investigator, materials, fatigue analysis)**

The participants wish to gratefully acknowledge the guidance and support provided by Jerry Gibbs, DOE/EERE/OVT, and Ray Johnson, ORNL.

Proposed Future Work

- **Remainder of FY 2010:**
- **Continue fatigue testing of specimens containing EDM notches to study crack nucleation in current high-pressure fuel injector nozzle materials.**
- **Develop a method for conducting fatigue tests in diesel fuel environments**
- **Conduct a fracture toughness study of current and candidate nozzle alloys.**
- **FY 2011:**
- **Extend fatigue testing of specimens containing EDM notches to study the process of crack nucleation in promising candidate alloys for high-pressure fuel injector nozzles.**
- **Complete the final report by collaboration between the CRADA partners ORNL and Caterpillar, with input from the candidate alloy supplier, CARTECH.**

SUMMARY

- This project is a cooperative research and development agreement (CRADA) between ORNL and Caterpillar that also involves collaboration with a specialty steel supplier (CARTECH).
- The effort addresses the challenge of durable material selection for use in diesel engine high-pressure fuel injection systems.
- A critical aspect is nozzle alloy fatigue performance under multiple pressure pulses, and the role of microstructural features in the initiation and propagation of fatigue damage in highly-stressed components.
- Residual stress does not seem to present a serious concern for the initiation of fatigue damage in nozzle tips (sacks) in current alloys.
- A better understanding of the applied stress versus fatigue life was obtained for the current nozzle material, and future plans include extending this understanding to candidate alloys with improved performance.