Materials for High Pressure Fuel Injection Systems

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Principal Investigators

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POSTER PRESENTATION: May 10, 2011

Project ID: PM021

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Overview

Timeline

- Project start date: July 2008
- Project end date: September 2011
- Percent complete: 85%

Budget

FY	ORNL	CAT *
2008	225K	225K*
2009	225K	225K*
2010	225K	225K*
2011	200K	200K*

* In-kind

Barriers

Barriers addressed:

- By 2015, develop materials and materials processing techniques to enable the development of fuel injection systems with pressures of over 2800 Bar (FY 2011-15 MYPP Goal).
- Injector nozzle materials must withstand billions of high-pressure pulses.

Partners

- Project lead: ORNL
- Caterpillar® Inc. (CRADA Partner)

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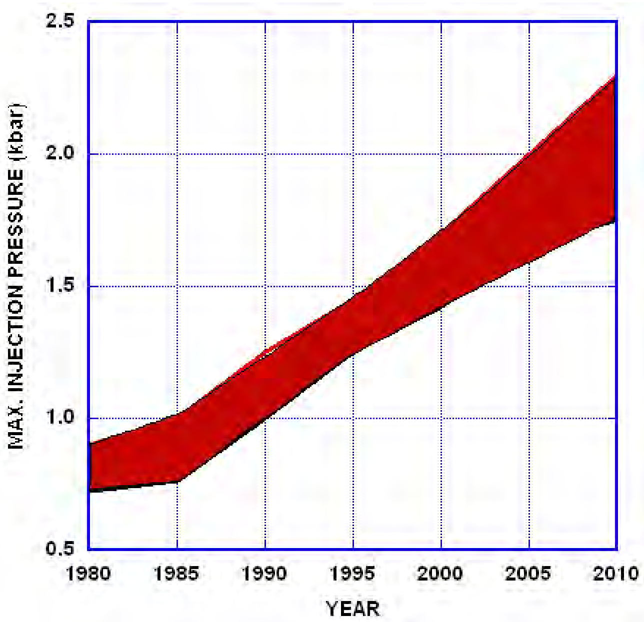
Relevance

- Diesel engine designers are driven to optimize engine designs for fuel efficiency and to meet government emissions requirements.
- The fuel injector nozzle, with its pattern of fine spray holes, is key to precise fuel metering to control combustion characteristics and reduce emissions.



- Rising injector design pressures present four key challenges for materials and manufacturing:
  - Challenge 1: Holes must maintain dimensional tolerances and flow characteristics for hundreds of millions, or even billions 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: Concerns over the effects of residual stress state, hole bore characteristics, and metallurgy on high-cycle fatigue of nozzle tips
  - Challenge 4: Will current injector tip materials withstand high pressures, and if not, what alternative materials may be suitable?

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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 characterization tools to link the microstructures of high-pressure fuel injector alloys to their resistance to fatigue crack initiation and growth in ambient and fuel-laden environments.

Milestones for FY '09 - '11 (Slide 1 of 2)

Month / Year	Milestone
Jan / 2009	☑ Hole metrology: Developed methods to measure the roughness and surface features of the interior of spray holes.
Mar / 2009	☑ Evaluated ability for x-rays and neutron methods to measure residual stresses in injector tips: Using 3 different national laboratory facilities, investigated residual stresses in injector tips near.
Jun / 2009	☑ Designed and developed fatigue-testing method(s) to simulate high-pressure tip loading: Develop fatigue tests to simulate the expected stress states in nozzles.
Jan / 2010	☑ Install a tele-microscope to image fatigue crack growth in situ: Photographed fatigue cracks propagating from the edges of a defect.
Feb / 2010	☑ Characterize the fine structure of spray hole walls using transmission electron microscopy: Using focused ion beam methods, investigate the structure of EDM recast layers.

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Milestones for FY '09 - '11 (Slide 2 of 2)

Month / Year	Milestone
Mar / 2010	☑ Determine the smooth fatigue performance of materials proposed for high-pressure nozzles: Conduct smooth fatigue tests to establish crack initiation sites in the absence of spray holes.
Sep / 2010	☑ Complete initial characterization of fatigue specimens containing notches. Investigate effects of simulated spray holes (EDM) on fatigue life of injector nozzle alloys.
July / 2011	☐ Conduct fatigue crack growth tests on notched specimens in the presence of diesel fuel. Investigate effects of diesel fuel on crack growth in notched fatigue specimens.
Sep / 2011	☐ Complete project and submit final report. Report on the microstructure, properties, and fatigue characteristics of candidate high-pressure fuel injector alloys.

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. (Years 1-3)

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. (Year 1)

3) Using laboratory tests, investigate the **fatigue behavior of steels for fuel injector tips**, as affected by the presence of fine holes and fuel environments. (Years 2-3)

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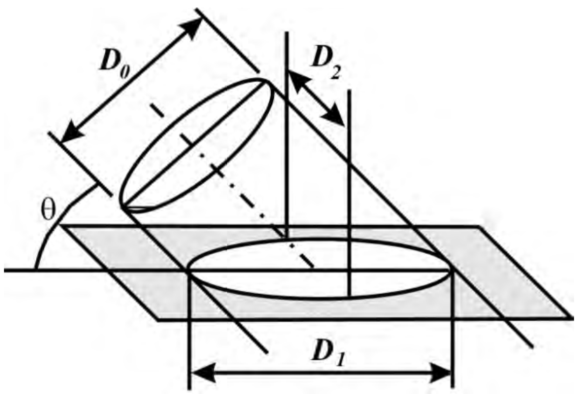
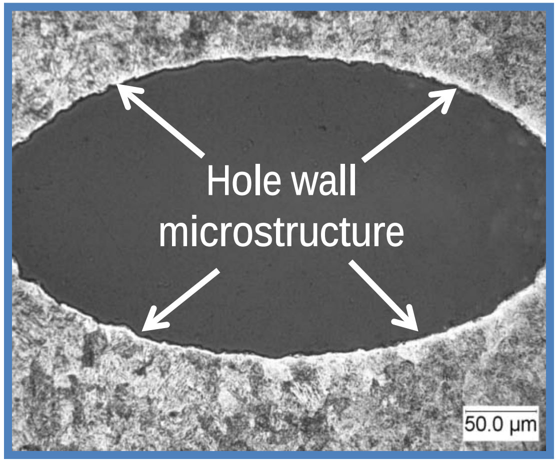
Technical Accomplishments and Progress

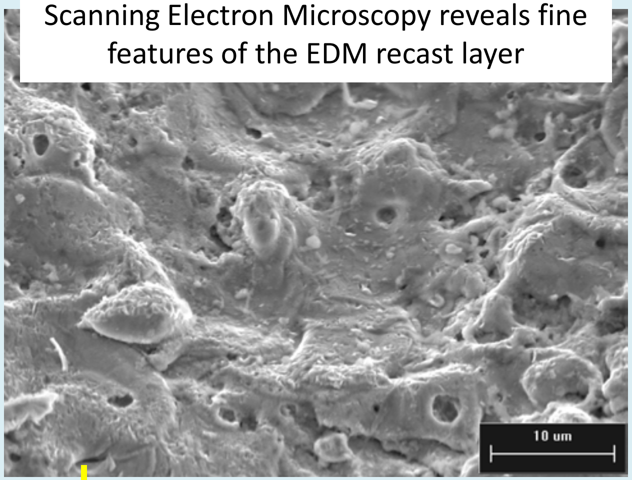
1) Characterization of hole microstructures and hole walls
2) Characterization of hole morphology and interior roughness
3) Measurements of residual stress by x-ray and neutron scattering
4) Studies of micro- and nano-mechanical properties of hole walls
5) Studies of fatigue crack initiation and growth in nozzle alloys with and without simulated spray holes

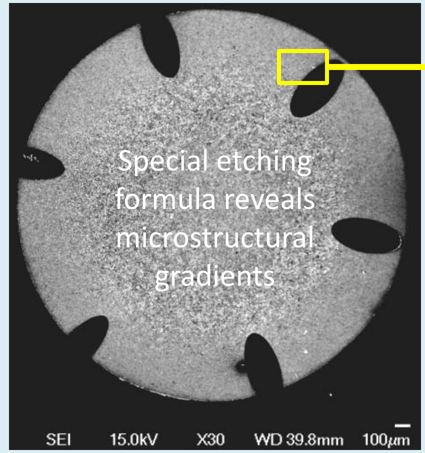




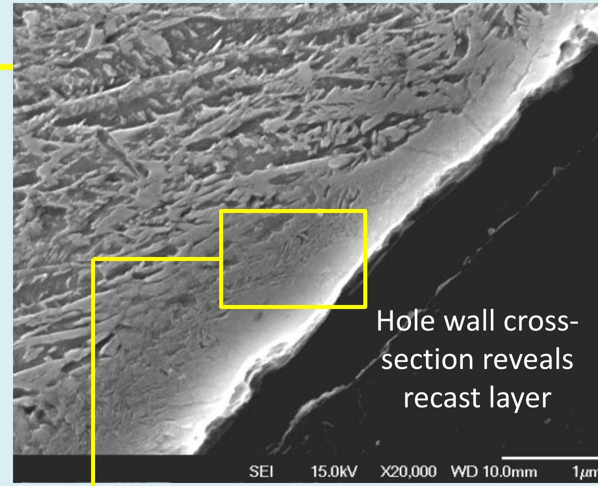
Hole Wall Microstructure Characterization

Scanning Electron Microscopy reveals fine features of the EDM recast layer



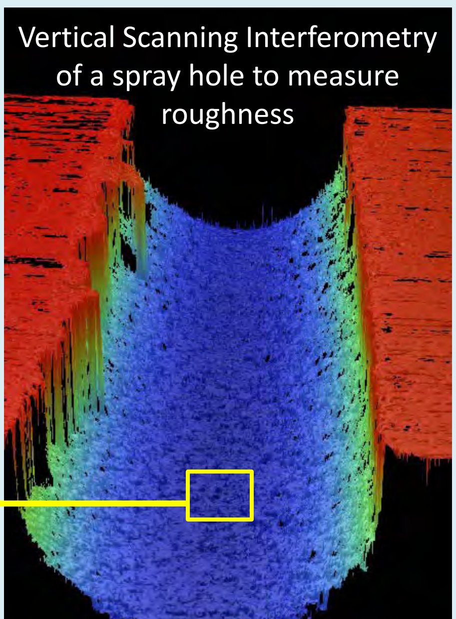


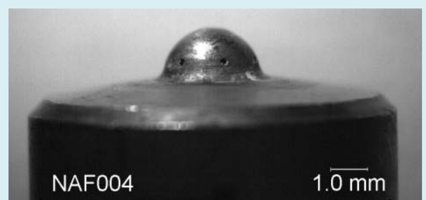
Special etching formula reveals microstructural gradients



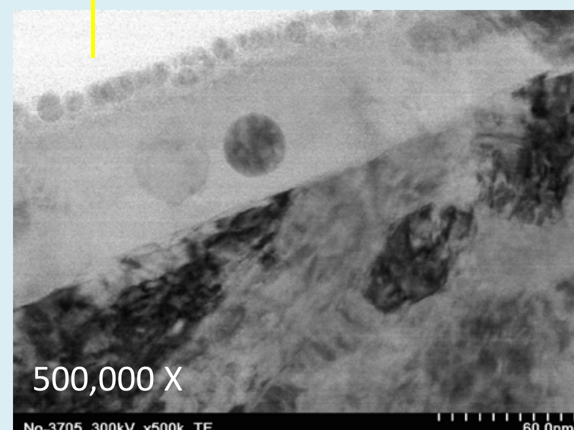
Hole wall cross-section reveals recast layer

Vertical Scanning Interferometry of a spray hole to measure roughness





Focused Ion Beam (FIB) used to section recast layer to enable Transmission Electron Microscopy



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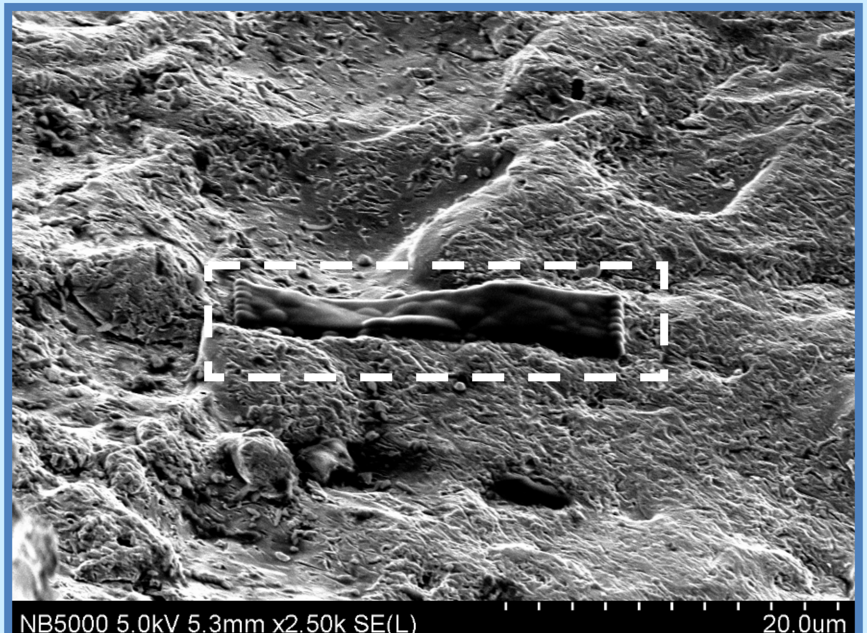
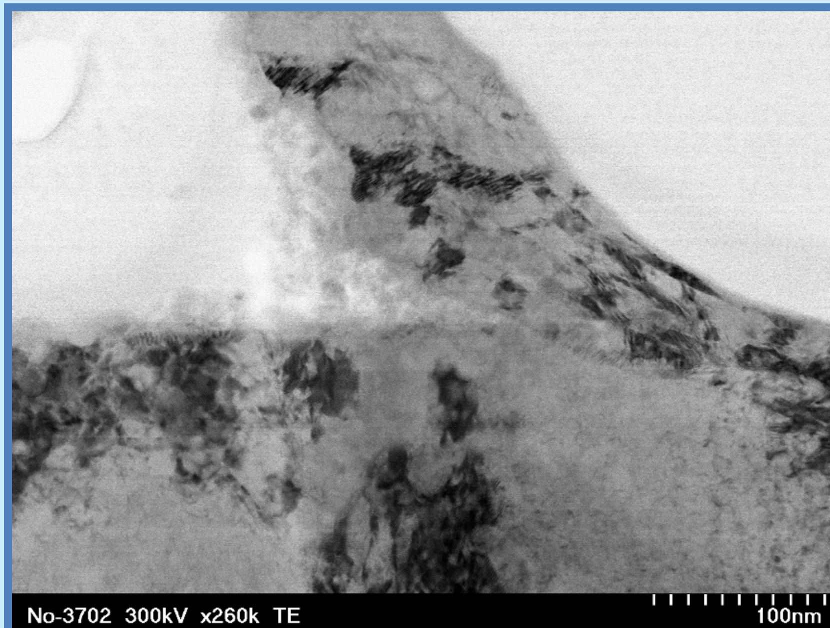
Nanostructures in hole walls

A focused ion beam (FIB) was used to remove a slice from the recast zone in a spray hole wall for transmission electron microscopy studies (Coffey/Howe)

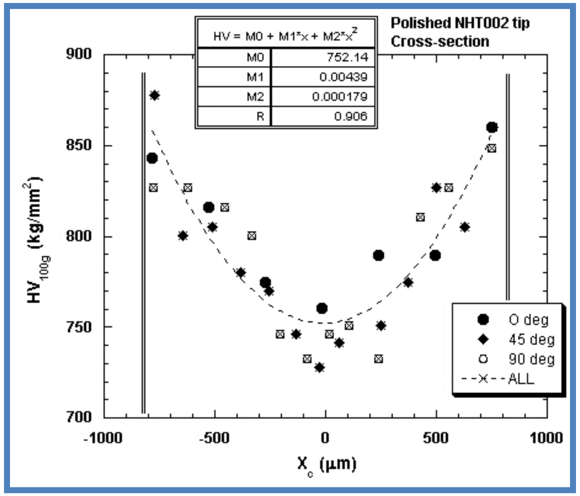


FIB'ing a slice from the hole wall after capping it with a metallic film



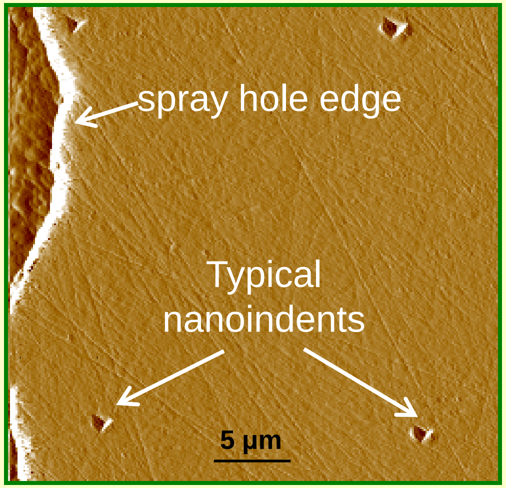
Cross-section of the slice showing fine structure in the re-cast zone

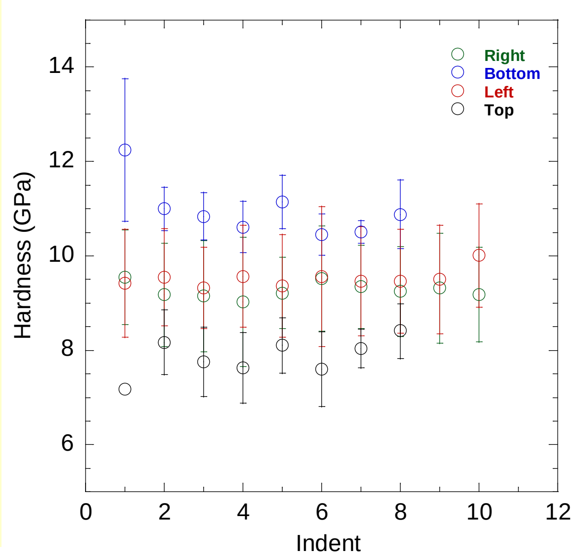
Micro- and Nano-Mechanical Properties of Nozzle Walls and Recast Regions at Holes



Microindentation hardness data (above) indicates localized mechanical properties gradients through the nozzle walls.

Nano-indentation hardness data (at right) were obtained with a Berkovich tip: Loading/ Unloading Rate = 500 µN/sec, Max Load = 5000 µN, Dwell Time = 10 sec





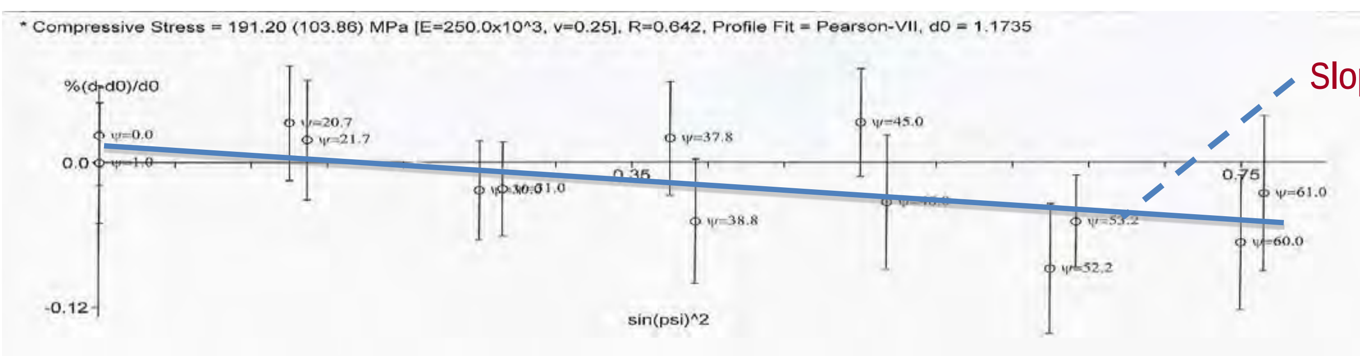
Each plotted point represents 10-15 indents

- ❑ Statistical analysis (ANOVA; α=0.5) on the Left and Right, and the Top side of the cross-sectioned hole indicate that there is no hardness gradient between the edges of the spray hole and the bulk material.
- ❑ While the recast layer is microstructurally different from the bulk, its nano-mechanical response was not .

Residual Stress Studies of Nozzles

Three DOE X-ray and neutron diffraction stress mapping facilities were used to study the feasibility of achieving the spatial dimensions needed to characterize specific locations on 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 (*see figure below*)
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.



Slope indicates slightly compressive stress

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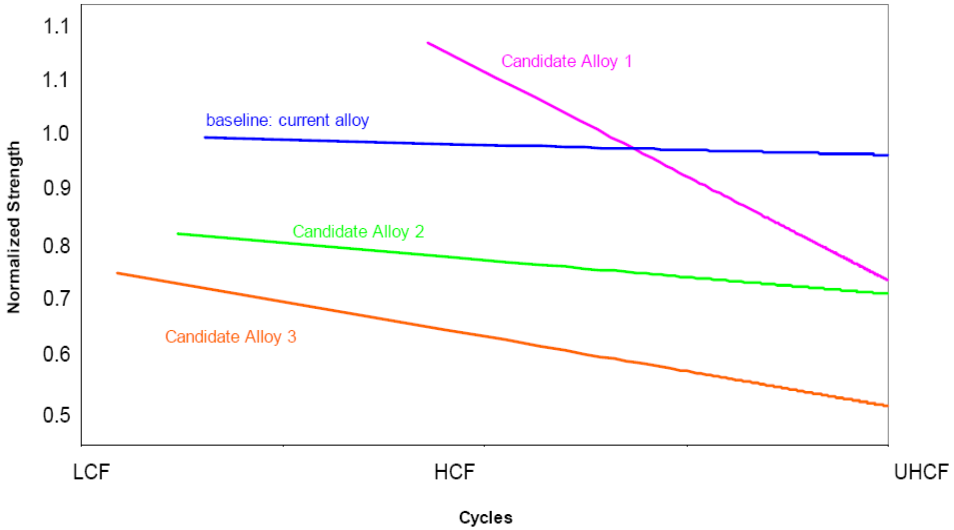
Fatigue Properties and microstructure of current and candidate materials

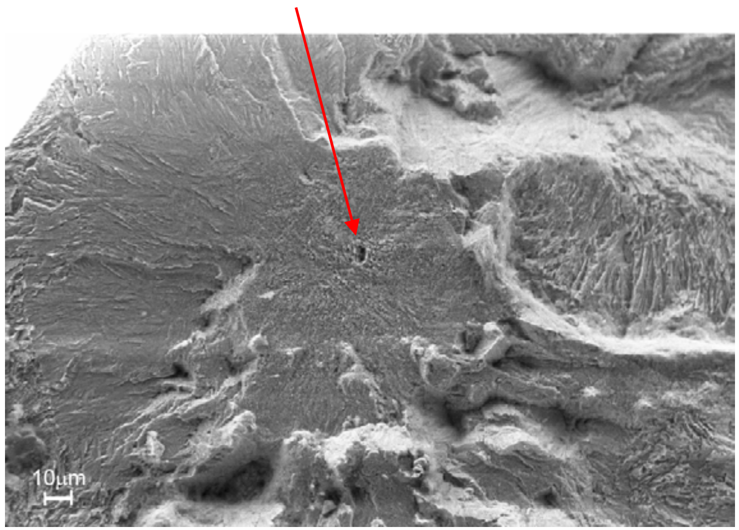
Rotation Bending Fatigue (RBF) tests were performed at Caterpillar on current and candidate materials. Failure analysis and microstructure studies were carried out and related to their fatigue performance.



Normalized RBF test results of current and candidate fuel injector materials.

(LCF = low cycle fatigue, HCF = high-cycle fatigue, UHCF = ultra-high cycle fatigue)

Fatigue failure initiated at sub-surface inclusion



SEM image of an UHCF fracture surface of a surface-treated candidate material.

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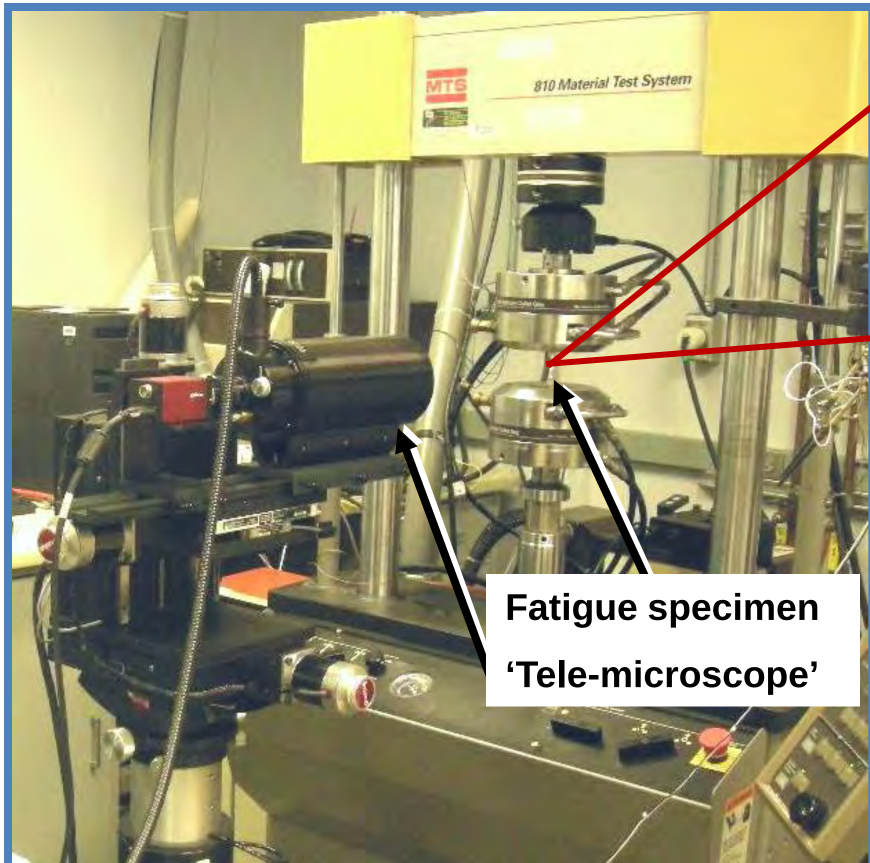
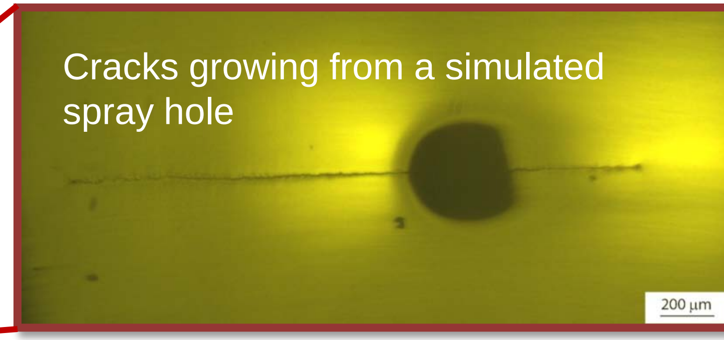
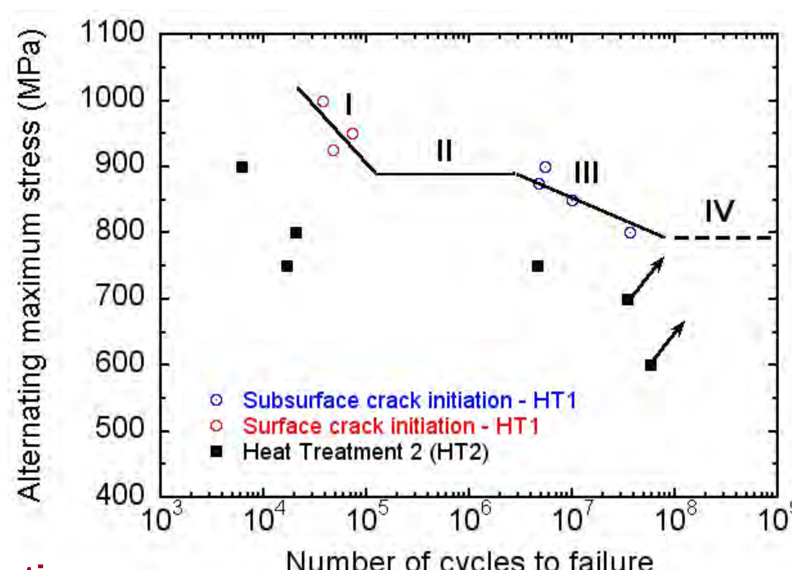
Fatigue life and *in situ* crack initiation studies at ‘model’ EDM spray holes







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

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Summary of Annual Progress

This Cooperative Research and Development Agreement (CRADA) is aimed at characterizing materials that can withstand the demanding stress conditions of high-pressure diesel engine fuel injectors. Highlights of annual progress:

- (FY 08) Initial characterization of fuel injector spray holes features.
- (FY 09) X-ray and neutron-based methods investigated 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 09-10) A fatigue test protocol was developed and used to study fatigue crack initiation and propagation in nozzle materials, with and without simulated spray holes. A dual-mode of crack initiation was discovered in the alloy steel.
- (FY 10) Microstructures at the walls of spray holes were first studied using transmission electron microscopy and focused ion beam specimen preparation.
- (FY11) Current FY progress: nano-indentation studies, notched fatigue studies, extension of fatigue studies to the effects of diesel fuel environments.

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Collaboration and Coordination with Other Institutions

- **ORNL and Caterpillar Inc.** are partners in a multi-year Cooperative Research and Development (CRADA). Caterpillar provides components for study and heat-treated materials testing, shares prior characterization and mechanical property data for current and candidate materials for advanced fuel injectors.

Joint Publication / Presentations

- A. Shyam, P. J. Blau, and M. J. Pollard "The very high cycle fatigue behavior of tool steel materials for diesel fuel injectors," accepted for the *5th International Conference on Very High Cycle Fatigue*, Berlin, Germany (June 28-July 1, 2011).

- P. J. Blau, J. Y. Howe, D. Coffey, R. M. Trejo, L. R. Walker, B. C. Jolly, and N. Yang, "Microstructure, Morphology, and Nanomechanical Properties Near Fine Holes Produced by Electro-Discharge Machining," in preparation for the journal *Materials Engineering and Performance* (2011).

- A. Shyam, P. Blau, T. Jordon and N. Yang, "The fatigue behavior of steels for fuel injection applications," in preparation for ASM Materials Science and Technology Conference and Expo, Columbus, OH (October 16-20, 2011).

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Acknowledgments

- ORNL
  - Peter Blau (co-principal investigator, metallurgical characterization)
  - Cam Hubbard (residual stress measurement and analysis)
  - Amit Shyam (fatigue and fracture testing and modeling)
  - Randy Parten (coordinate measurement and precision grinding)
  - Rosa Trejo (nanoindentation measurements)
  - Dorothy Coffey (FIB specimen preparation)
  - Jane Howe (TEM studies)
- CATERPILLAR:
  - Mike Pollard (prior principal investigator, fatigue, heat treatment effects)
  - Nan Yang (current principal investigator, fatigue studies)

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 2011:

- **Effects of Heat Treatment on Fatigue**: Continue fatigue testing of specimens containing EDM notches to study crack nucleation in current high-pressure fuel injector nozzle materials under heat-treated conditions.
- **Environmental Effects on Fatigue**: Investigate effects of diesel fuel surroundings on the initiation and propagation of fatigues near simulated spray holes.
- **Final Report**: Complete the project final report by CRADA partners ORNL and Caterpillar.

Proposed for FY 2012 – 2013 (new effort)

- **Next-Generation Injector Materials**: Application of the tools and experimental methods developed during the current project to study fatigue initiation and growth in next-generation alloys able to withstand maximum fuel injection pressures well in excess of 3000 bars in hot environments.

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SUMMARY

- This project represents a cooperative research and development agreement (CRADA) between ORNL and Caterpillar, aimed at an issue critical to raising energy efficiency of advanced diesel engines.
- 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.