Materials for High Pressure Fuel Injection Systems

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Overview

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

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.

Budget

<table>
<thead>
<tr>
<th>FY</th>
<th>ORNL Planned</th>
<th>ORNL Rec’d</th>
<th>CAT Planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>225K</td>
<td>225K</td>
<td>225K*</td>
</tr>
<tr>
<td>2009</td>
<td>225K</td>
<td>225K</td>
<td>225K*</td>
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<tr>
<td>2010</td>
<td>225K</td>
<td>152K</td>
<td>225K*</td>
</tr>
<tr>
<td>2011</td>
<td>225K</td>
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<td>225K*</td>
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</tbody>
</table>

* In-kind

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.
<table>
<thead>
<tr>
<th>Month / Year</th>
<th>Milestone</th>
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<tbody>
<tr>
<td>Jan / 2009</td>
<td><strong>Hole metrology</strong>: 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.</td>
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<tr>
<td>Mar / 2009</td>
<td><strong>Evaluate ability for x-rays and neutron methods to measure residual stresses in injector tips</strong>: Using facilities at ORNL, as well as other national laboratories, establish the feasibility of mapping residual stresses in injector tips near spray holes.</td>
</tr>
<tr>
<td>Jun / 2009</td>
<td><strong>Design and develop fatigue-testing method(s) to simulate high-pressure tip loading</strong>: Develop fatigue tests that simulate the expected stress states, and which can be applied to investigate spray hole characteristics and alternative nozzle material choices.</td>
</tr>
<tr>
<td>Sep / 2009</td>
<td><strong>Determine the relative fatigue performance of candidate materials for high-pressure tips</strong>: <em>(Delayed until July 2010, due to the non-availability of specimen materials).</em></td>
</tr>
<tr>
<td>Month / Year</td>
<td>Milestone</td>
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<tr>
<td>Jan / 2010</td>
<td>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.</td>
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<tr>
<td>Feb / 2010</td>
<td>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.</td>
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</table>
A Three-Pronged Approach

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
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.

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

Dimensions are in inches except where mentioned

- 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 $\sigma_{\text{max}} < 900$ 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.

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.