Durability of Diesel Engine Materials

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PM 9104

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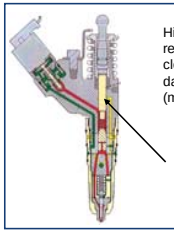
21CTP Technical Goal: **Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system efficiency from ~42% today to 50% by 2010.**

Project Objectives
Quantify, model, and prevent surface damage in diesel engine components like EGR valve actuators and fuel injector plungers that must operate in low S fuels.

FY 2005 Focus
Test the durability of advanced materials and surface treatments, and develop a multi-stage model for the initiation and propagation of scuffing in fuel injectors.

Planned Duration
October 2001 to September 2005

DOE Funding/Industry Cost Share
FY04: $200K; FY05: $180K



High-performance fuel injectors require precise plunger-bore clearances (cannot tolerate scuffing damage) and must avoid seizure (maintain low sliding friction).

Courtesy of Cummins Engine Co.

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Accomplishments
- Applied thermal oxidation to greatly reduce the wear of titanium alloys for use in diesel engine components. (3/2005)
- Based on test data, developed a multi-stage scuffing model that includes the role of surface finish and lubricant films in the localized initiation and propagation of surface damage. (9/2005)

Significant Future Milestones
Project will be completed in FY 2005. Planned follow-on effort to enhance energy-efficiency of valve train components (valve seats and guides) through the use of advanced materials.

Project ID/Agreement ID	Program Structure	Sub-Program Element	R&D Phase	Date
PM_9104	Materials Technology	HV Propulsion Materials	Applied Research	8-11-05

Objectives

- Improve the durability and performance of selected moving parts in diesel engines using of advanced materials like ceramics and composites.
- Understand the fundamental nature of surface damage and its propagation in specific engine components.
- Provide guidance for selecting materials and surface finishes for energy-efficient, durable diesel engine parts.

Approach

- Identify areas in diesel engines where durability significantly impacts fuel-efficiency / emissions.
- Determine the primary failure modes of key components.
- Develop test methods and analyses based on a multi-disciplinary understanding of both materials and lubricant behavior.
- Apply the specially-designed tests, analyses, and models to current and candidate materials / surface treatments that have the potential to improve durability.
- Summarize, analyze, and distribute findings to U.S. industry and other interested parties.

Lowering friction and wear between moving parts in diesel engines offers opportunities to improve fuel-efficiency and durability

- Main bearings
- Cam shaft
- Piston rings / cylinder liners
- Cam roller followers
- Fuel injector plungers
- EGR system components*
- Valve guides / seats

Prior research
This project
Planned

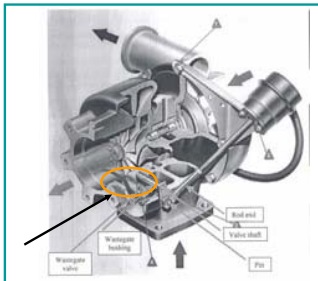
Caterpillar C-15 Diesel Engine

*** Not all engine manufactures use EGR**

Relevance to 21 CT Goals

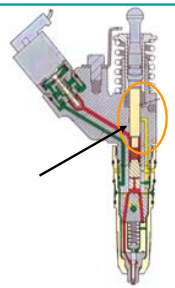
- **21 CT Technology Goals**:
  - Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system fuel efficiency by 20% by 2010.
  - Research and develop technologies which will achieve a stretch thermal efficiency goal of 55% in prototype engine systems in 2012.
- **Impact**: Developed new test methods for scuffing, in addition to data and analyses to support the selection and use of advanced materials, surface treatments, and coatings to reduce friction and increase durability in both fuel and EGR systems.
- **Roles of 21 CT partners**:
  - Provided certain fuel system components for comparative, baseline testing (Cummins)
  - Held periodic discussions (Caterpillar, Cummins, DDC).
  - Came to ORNL to use our unique testing equipment for EGR studies (DDC)
- **Additional Benefits**:
  - Insights into the mechanisms and progression of surface damage on bearing surfaces sensitive to scuffing and wear.
  - Revealed benefits of a new, inexpensive surface treatment for Ti alloys to significantly reduce wear in cylinder liner environments.

Emphasis has been on EGR system components and fuel injector plungers



FY 2001– 3. Developed a high-temp scuff testing apparatus and evaluation criteria to quantify mat'l performance.

FY 2003- 5. Worked with DDC and then Stellite Corp. in evaluating candidate materials.



FY 2002– 4. Developed a pin-on-twin test apparatus and conducted tests.

FY 2003- 5. Developed scuffing transition maps and a model for the evolution of scuffing damage.

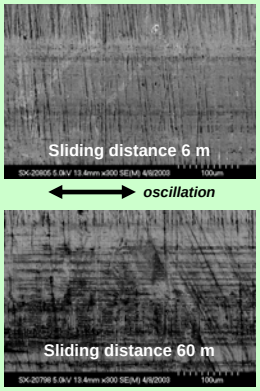
Technical Accomplishments/ Progress/Results

1) **Waste Gate Bushings**. Brief summary of the work on high-temp scuffing of EGR components (arising from previous FY).

2) **Fuel Injector Scuffing**. Method for characterizing and modeling the scuffing characteristics of promising new fuel injector materials.

3) ***Recent highlight***: Promising new surface treatment for Ti alloys in bearings – thermal oxidation

What is scuffing, and why is it important for energy-efficient operation of diesel engines?



Progressive scuffing of 52100 steel

Scuffing is a form of *surface damage* that can degrade engine performance.

In valve guides, fuel injectors, waste-gate bushings, scuffing can cause *seizure* or produce *unstable motion*.

It can alter surface roughness and *reduce the effectiveness of lubrication*, thus increasing friction and lowering energy efficiency.

Can *change the fit* between mating surfaces, causing leakage or loss of compression.

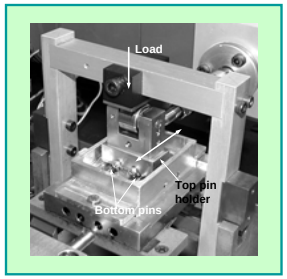
Its on-set is very hard to predict, and when it starts it can spread like a cancer from one part of a surface to another.

Waste Gate Bushing (FY 2003-05)

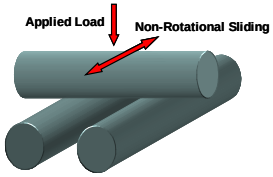
- Developed a 'bow-tie' test apparatus (600º C) and analysis method that weighs 6 or more separate criteria to rank overall high-temperature performance.
- Test method used by DDC and they recommended it to their material supplier Deloro Stellite Corp. under the HTML User Program.
- Developed a high-temp. scuffing map to help in material selection.
- Methodology now under consideration for use by a major waste-gate actuator manufacturer.

Fuel Injector Scuffing (FY 2003-05)

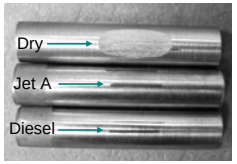
- Designed a test geometry to enable the use of plungers or test specimens
- Modified an existing friction testing machine
- Developed measurement methodology to characterize the extent of scuffing
- Tested candidate materials (metals, ceramics, cermets, coatings)
- Developed graphical and analytical methods to describe the initiation and progression of surface damage



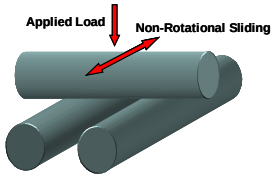
Crossed cylinders 'Pin-on-Twin' Test

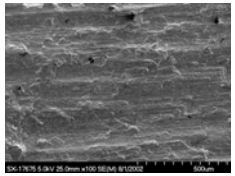


Fuel lubricity produced different levels of surface damage on 52100 steel (typ. Injector bore)

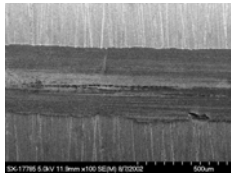


Lower specimens

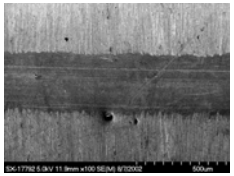




Dry

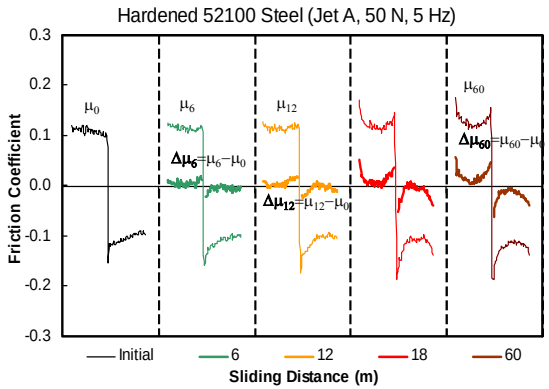


Jet A

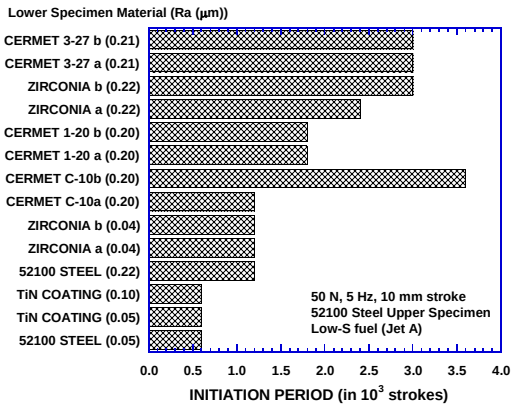


#2 Diesel

The onset of scuffing was detected by comparing digital friction records for individual strokes

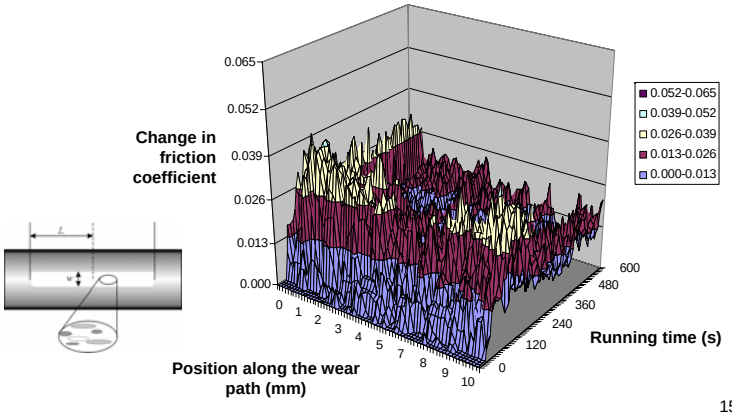


The initiation period for scuffing varied depending on material combination and surface finish

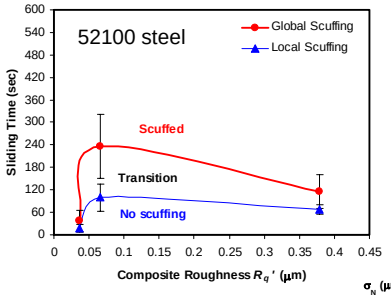


3D Friction Transition Maps

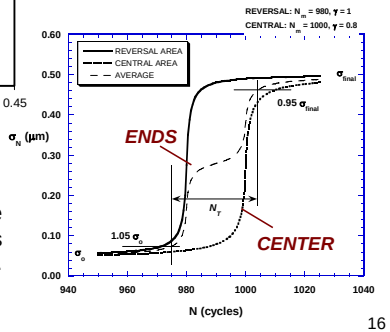
Portrays the change in friction coefficient relative to the first stroke and enables the onset and progression of scuffing to be determined.



The optimum surface finish to lengthen the damage propagation period can be represented



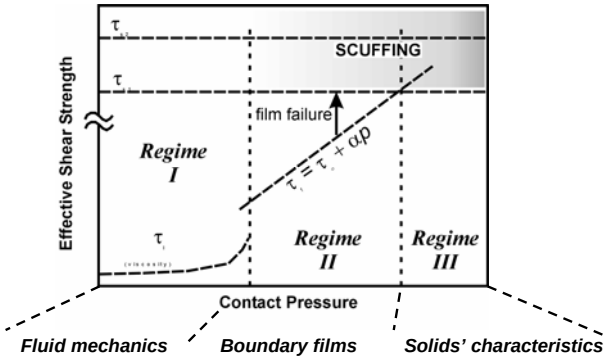
Pin-on-twin experiments showed that scuffing begins locally then spreads across the surface.



Once local scuffing begins, the time to reach global scuffing conditions can be accounted for in the model.

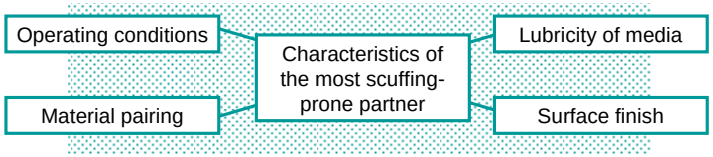
The scuffing model includes effects of lubricant and material characteristics

The 3 regimes account for a transition from liquid film control to interface shear strength control by the properties of the solids.



Fuel Injector Scuffing (FY 2003-05)

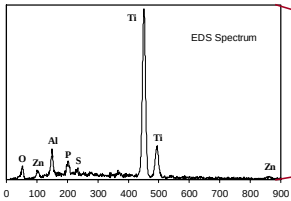
- Developed a 'pin-on-twin' scuffing test.
- Conducted tests on metals, ceramics, cermets, and hard coating in various fuels including low-S fuels.
- Developed a data collection and reduction method to identify the on-set and propagation of scuffing.
- Developed scuffing transition maps and a multi-disciplinary 3-stage model.



Highlight –Thermal Oxidation (TO) Process Can Enable Ti Alloys to be used as Bearing Surfaces

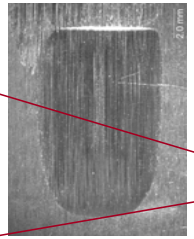
- Simple heat treatment grows oxide films on Ti alloy reduces friction by 70% and wear rate (ring and liner test) by from **40,000 to 100,000 times**!

- Bare Ti does not react with or benefit from anti-wear additives in formulated diesel oil, but the TO surface layers do!



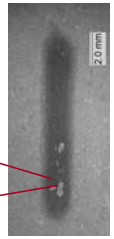
Bare T-6Al-4V

130 N, 11 min.



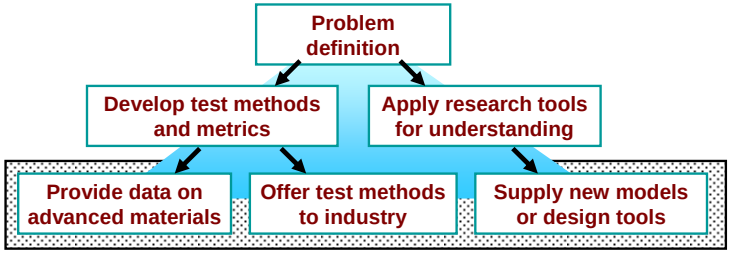
TO Ti-6Al-4V

240 N, 6 hours!



Technology Transfer

- Continuing information exchange via dialogs and visits with engine companies and their suppliers.
- Presentation and publication of results.
- Working with diesel company engineers and suppliers under the HTML User Program.



Future Work

- Project ends in FY 2005 with a final report containing the scuffing model, discussion of optimized injector plunger surface finishes, and guidance for anti-scuffing material selection (under preparation).
- A new project to address valve train friction and durability issues in diesel engines has been planned.
- Would like to explore the benefits of thermal oxidation treatment to enable use of Ti in engines.

Publications and Presentations (1 of 2)

PUBLICATIONS

P. J. Blau (2001) "Friction and wear of a Zr-based amorphous metal alloy under dry and lubricated conditions," *Wear*, Vol. **250**, pp. 431-434.

P. J. Blau (2003) Transient Scuffing of Candidate Diesel Engine Materials at Temperatures up to 600 ºC, ORNL Tech Report, ORNL/TM-2003/142, March 2003, 19 pp.

P. J. Blau, J. J. Truhan, and J. Qu (2004) Scuffing Transition Diagrams for Fuel Injection System Materials, project milestone report.

J. Qu, John J. Truhan, P. J. Blau (2005) "Application of the ASTM Loop Abrasion Test to Cylindrical Specimens," *ASTM J. of Testing and Evaluation,* Vol. 33, No. 1, Jan. 2005, JTE12508

J. Qu, J. J. Truhan, P. J. Blau (2005) "Evaluating Candidate Materials for Heavy Duty Diesel Fuel Injectors Using a 'Pin-On-Twin' Scuffing Test," *Tribology International*, Vol. 38, No. 4, pp. 381-390.

J. J. Truhan, J. Qu, P. J. Blau (2005) "A Rig Test to Measure Friction and Wear of Heavy Duty Diesel Engine Piston Rings and Cylinder Liners using Realistic Lubricants," *Tribology International*, Vol 38 (3), pp 211-218.

J. Qu, J. J. Truhan, P. J. Blau (2005) Scuffing Transition Diagrams for Heavy Duty Diesel Fuel Injector Materials in Ultra Low-Sulfur Fuel-Lubricated Environment," *Wear*, Vol. 259, pp 1031-1040.

P. J. Blau (2005) "On the nature of running-in," invited paper for Tribology International – in press.

Qu, J., Truhan, J.J., Blau, P.J. (2005) "Detecting the Onset of Localized Scuffing with the Pin-on-Twin Fuel-Lubricated Test for Heavy Duty Diesel Fuel Injectors," *SAE International Journal of Engine Research*, Vol. 6, No. 1, pp. 1-9

Publications and Presentations (2)

PRESENTATIONS

J. Qu, P. J. Blau and J. Truhan (2003) "Detecting of the Onset of Localized Scuffing with the Pin-on-Twin Fuel-Lubricated Test for Heavy Duty Diesel Fuel Injectors," pres. at Boundary Lubrication for Transportation, Copper Mountain, CO, August 3-8.

J. Qu, P.J. Blau, R. Ott, and J. Truhan (2003) "The Development of a Pin-on-Twin Scuffing Test to Evaluate Materials for Heavy Duty Diesel Fuel Injectors," poster, *2003 International Conference on Wear of Materials*, Washington, DC.

P. J. Blau (2003) "Challenges for the application of engineered surfaces to tribosystems with multiple contact modes," invited pres. at the symposium on Integrated Surface Engineering, ASME/STLE Tribology Conference, Ponte Vedra, FL, October 28.

P. J. Blau (2005) "A Retrospective View of Wear Research and Some Emerging Challenges," pres. at World Tribology Congress III, Sept. 2005, Washington, DC.

P. J. Blau and B. C. Jolly (2005) "Wear of truck brake lining materials using three different test methods," pres. at Wear of Materials 2005, April.

J. Qu, J. J. Truhan, P. J. Blau (2005) Scuffing Transition Diagrams for Heavy Duty Diesel Fuel Injector Materials in Ultra Low-Sulfur Fuel-Lubricated Environment," pres. at Wear of Materials 2005, San Diego, April.

P. J. Blau (2005) "A Retrospective View of Wear Research and Some Emerging Challenges," pres. at World Tribology Congress III, Sept. 2005, Washington, DC.