## F. Durability of Diesel Engine Component Materials

*Peter J. Blau with Jun Qu and John J. Truhan Jr**
*Oak Ridge National Laboratory,*
*P. O. Box 2008, Mail Stop 6063*
*Oak Ridge, TN 37831-6063*
*(865) 574-5377; fax: (865) 574-6918; e-mail: blaupj@ornl.gov*
**University of Tennessee, Knoxville*

*DOE Technology Development Area Specialist: Dr. Sidney Diamond*
*(202) 586-8032; fax: (202) 586-2476; e-mail: sid.diamond@ee.doe.gov*
*ORNL Technical Advisor: D. Ray Johnson*
*(865) 576-6832; fax: (865) 574-6098; e-mail: johnsondr@ornl.gov*

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### Objective

- Enable the use of durable, lower-friction moving parts in diesel engines by developing test methods to simulate the environment in which engine parts operate, and by conducting structural characterization of promising new materials, surface treatments, composites, and coatings.

### Approach

- Identify diesel engine components that will require advanced materials or surface treatments in order to ensure durability while providing low-friction behavior. This work has focused on (a) wastegate bushings for exhaust gas recirculation (EGR) components and (b) fuel injector plungers.
- Identify materials, coatings, and/or surface treatments that have the potential to increase the durability of the selected engine components.
- Develop test methods to evaluate the performance of candidate materials under simulated use conditions.
- Develop graphical representations (scuffing control maps) of operating parameters and the wear response of the materials to those parameters.
- Analytically model the effects of applied parameters on the responses of leading candidate materials as a guide to materials development and application.

### Accomplishments

- Designed, built, and used a high-temperature oscillatory scuffing test system that operates at wastegate bushing temperatures (~ 600–700ºC).
- Conducted tests on a range of metallic alloys, ceramics, and coatings to determine which of these had the best durability under high-temperature conditions. Published a technical report on the findings.
- Developed a novel, pin-on-twin (PoT) scuffing test to evaluate fuel injector materials in diesel fuel and low-sulfur fuel. Prepared a mathematical model to more accurately calculate wear loss from parts with compound curvatures.
- Developed criteria for the onset of scuffing damage and evaluated traditional steel fuel injector materials as well as ceramics, advanced cermets, and hard coatings in diesel fuel and low-sulfur fuel.

### Future Direction

- Improve the design of the PoT test to enable more realistic simulation of the type of damage seen in fuel injector plungers.
- Develop a graphical representation of the surface damage conditions of fuel injector component materials (a scuffing map) to aid designers in selecting more durable materials.
- Use scuffing maps to model the evolution of localized surface damage and the degradation of component durability.

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## Introduction

The diesel engine industry faces the challenges of improving fuel efficiency while meeting federal emissions regulations. These challenges can be addressed by modifying the engine designs and electronic control systems for engines and by developing exhaust aftertreatments. Such modifications affect the mechanical, thermal, and chemical environments to which the engine materials are subjected, and the current structural materials may not perform as well as they did in previous designs.

The objective of this effort is to enable the selection and development of durable, lower-friction moving parts in diesel engines for heavy vehicle propulsion systems through the systematic evaluation of promising new materials, surface treatments, composites, and coating technologies. The current approach involves developing test methods, conducting microstructural analysis of candidate materials, mapping the effects of applied parameters on surface damage, and modeling.

In FY 2001, a test method was developed to study the high-temperature friction and wear characteristics of candidate EGR system materials. Selected metallic alloys, ceramics, and experimental materials were evaluated for their high-temperature scuffing behavior. In FY 2002, this effort was extended to include an investigation of the scuffing of fuel injector component materials. Laboratory tests were developed and refined to produce and measure the type of fine-scale surface damage that is observed in diesel engine fuel system parts. In FY 2003, research continued in two areas: (1) evaluating the effects of diesel fuel sulfur reductions on scuffing and (2) materials and coatings for high-temperature scuffing resistance in EGR components. Analysis of surface damage evolution in the microstructure was extended by taking advantage of a newly upgraded scanning acoustic microscope.

## Approach

The current approach to improving the surface durability of diesel engine components has involved extensive experimental evaluation, with particular focus on characterizing the behavior of current and candidate materials under conditions that simulate their use. The development of analytical models for surface degradation, especially for fuel injector components, is planned for FYs 2004 and 2005.

The focus on EGR components and fuel injector plungers was based on past and continuing discussions with diesel engine manufacturers. Before developing tests to evaluate materials for improved durability, it was first necessary to understand the conditions under which the surfaces of these component materials must perform in an operating diesel engine. The types of damage seen on engine components were reviewed in order to ensure that laboratory test methods would faithfully reproduce that kind of damage.

FYs 2000–2002 were devoted to selecting test geometries, constructing or modifying the test apparatus, and obtaining data on currently available commercial materials. Candidate new materials and surface treatments were then evaluated under the standardized test conditions to assess their potential. This remainder of this report summarizes FY 2003 research aimed at identifying the best materials choices for two engine components, wastegate bushings and fuel injector plungers.

## Results—Bushing Materials

A wastegate bushing consists of a pin that rotates inside a hollow bushing. It is used to open and close the valve that controls the recirculation of exhaust gases for emission control.[1] Smooth, uninterrupted motion is essential; but that is difficult to achieve considering that the surfaces of the parts are exposed to oscillatory motions at temperatures as high as 600ºC, at which traditional lubricants do not work. Previously, such components were made of austenitic stainless steels, but the demands created by new engine designs will require more cycles of operation and greater valve motion control. Therefore, alternative materials or coatings are needed.

A test apparatus was constructed to oscillate a cylindrical pin against a flat plate, producing a bow-tie-shaped wear area. The geometry was chosen for a variety of reasons: providing a linear contact, enabling the measurement of frictional torque, keeping the fixtures as simple as possible for high-temperature operation, and producing wear scars that resembled those on pins taken from actual components. Figure 1 shows a wear scar produced after 60 minutes of testing at 600ºC.

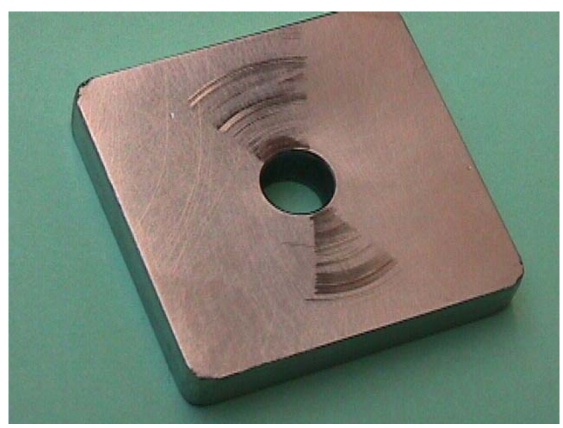

**Figure 1.** Scar on a test specimen showing the typical "bow-tie" shape.

In order to obtain a comprehensive characterization of the test material responses, several criteria were combined to rank their performance. These included average initial stage torque, standard deviation in initial torque, average final torque, standard deviation in final torque, pin specimen wear volume, and surface roughness of the lower specimen. A summary of the composite scores is given in Table 1. Stainless steels of types 303 and 304 were used as references but were not expected to be viable candidates. Test couples that involved an $Ni_3Al$ intermetallic alloy (IC-221) developed at Oak Ridge National Laboratory (ORNL) performed very well, as did the self-mated combination of commercial GallTough™ alloy. The ceramic-on-ceramic couple, which ranked fifth, did not perform as well because it did not form a lubricative surface oxide or a cushioning wear particle layer as did most other material pairs. Additional details of this work are provided in ORNL report ORNL/TM-2003/142, published in March 2003 (see the publications list).

**Table 1.** Rankings of the material combinations for 600°C scuffing resistance (1 = highest, 10 = lowest)

| Relative ranking | Pin material | Tile material |
|---|---|---|
| 1 | TTZ zirconia | $Ni_3Al$ alloy, IC 221 |
| 2 | GallTough™ | GallTough™ |
| 3 | Stellite 6B™ | $Ni_3Al$ alloy, IC 221 |
| 4 | Stellite 6B™ | Custom 465™ |
| 5 | TTZ zirconia | Silicon nitride GS-44 |
| 6 | Tribonic 20™ | $Ni_3Al$ alloy, IC 221 |
| 7 | SS 303 | SS 304 |
| 8 | Stellite 6B™ | SS 304 |
| 9 | TTZ zirconia | SS 304 |
| 10 | Stellite 6B™ | Pyromet 80™ |

SS = stainless steel
TTZ = transformation toughened zirconia ceramic
GallTough™ = a commercial, galling-resistant SS from Carpenter Steel
Stellite 6B™ = a cobalt-based, high-performance alloy
Custom 465™ = a commercial, high-performance SS from Carpenter Steel
Tribonic 20™ = a galling-resistant SS originally developed by AK Steel
Pyromet 80™ = a high-performance SS commonly used in engine exhaust valves

## Results—Fuel Injector Plunger Materials

A novel PoT test was developed to evaluate the scuffing tendencies of diesel fuel injector plunger materials in normal diesel fuel and low-sulfur fuel. In this test, a cylindrical pin oscillates crosswise on a pair of lower cylindrical pins, the axes of which parallel the direction of sliding contact (see Figure 2). The typical load is 50 N with a stroke length of 10 mm and a frequency of 5 cycles/s. This test produces two notch-like wear scars on the upper pin and two wear tracks on the lower pins. After a study of changes in surface roughness, weight loss, and other quantities, the change in friction force was selected as a workable criterion for the onset of scuffing. Detailed friction force changes were captured with a high-speed digital data acquisition system (500 data/s).

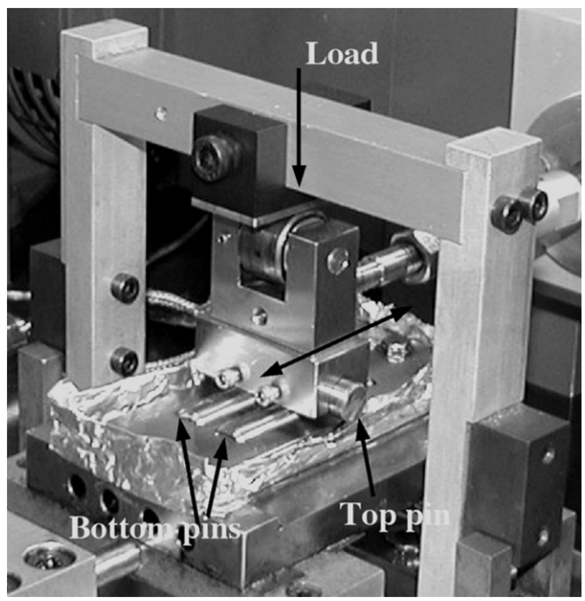


**Figure 2.** Specimen arrangement used for the pin-on-twin test.

The wave form for the friction-vs-time trace of the first stroke is subtracted from that for individual strokes obtained at longer and longer sliding distances. When a significant difference is detected in the pattern, scuffing is said to have initiated. Digital records also revealed that scuffing in most material combinations initiates at the ends of the stroke and spreads inward. This is consistent with the lubrication concepts developed by German investigator R. Stribeck, who showed that friction of lubricated contacts is related to viscosity, velocity, and contact pressure.[2] In reciprocating sliding (for the PoT) the friction force is lowest in the center of the stroke where the sliding speed is highest; thus damage initiates at the stroke ends.

A variety of materials was evaluated using the PoT test in several lubricants: mineral oil, diesel fuel 2, and Jet A aviation fuel, a surrogate for low-sulfur fuel. Initial tests were performed on typical plunger materials such as hardened bearing steel (Type 52100). More recent experiments focused on ceramics, cermets ($Ni_3Al$ matrix with TiC particles, obtained from ORNL and Southern Illinois University), and hard-coated (TiN) tool steel materials obtained from a commercial source. Table 2 lists recently evaluated candidate material combinations and their relative resistance to scuffing initiation, as determined by friction changes in the PoT test procedure. The upper oscillating pin was hardened 52100 steel in each case. Test results using candidate plunger materials for the upper pin instead of the lower twins has produced different results, and the latter type of test is undergoing further analysis to establish the standard protocol for further experiments.

**Table 2.** Material combinations and relative scuffing initiation time

| Twin pins material | Diesel 2 fuel | Low-S fuel |
|---|---|---|
| 52100 | M | M |
| Zirconia (TTZ) | L | M |
| Cermet (C-10) | M | M |
| Cermet (SIU 1-20) | M | L |
| Cermet (SIU 3-27) | S | M |
| TiN-coated steel | S | S |

S = short time (within the first 20 m sliding distance)
M = intermediate time (within 20–36 m sliding distance)
L = relatively long time ( > 50 m sliding distance)
TTZ = transformation toughened zirconia ceramic
C-10 = experimental cermet containing a $Ni_3Al$ matrix and TiC particles
SIU = compositions prepared at Southern Illinois University

## Conclusions

- An intermetallic $Ni_3Al$ alloy coupled with zirconia represents an attractive combination for high-temperature scuffing resistance in EGR applications

- Using a new PoT test and a differential friction trace-based scuffing criterion, ceramics, cermets, and hard coatings were evaluated for use in fuel injection systems. Cermets appear promising for this application and will be further investigated during the next fiscal year.

- Future plans include the development of scuffing maps and models to help select materials for reciprocating contacts.

## References

1. B. Bhushan, ed., *Modern Tribology Handbook*, Vol. 2, CRC Press, pp.1231–1269, 2001.

2. R. Stribeck, “Die Wesentlichen Eigenschaften der Gleit- und Rollenlager,” *Z. Verein. Deut. Ing.*, **46**(38), 1341–1348, 1902.

## Publications and Presentations

P. J. Blau, *Transient Scuffing of Candidate Diesel Engine Materials at Temperatures up to 600°C*, ORNL/TM-2003/142, Oak Ridge National Laboratory, 2003.

Jun Qu, Peter J. Blau, and John Truhan, "Detecting of the Onset of Localized Scuffing with the Pin-on-Twin Fuel-Lubricated Test for Heavy Duty Diesel Fuel Injectors," presented at Boundary Lubrication for Transportation, Copper Mountain, CO, August 3–8, 2003 (to be included in the proceedings).

J. Qu, P. J. Blau, R. Ott, and J. Truhan, "The Development of a Pin-on-Twin Scuffing Test to Evaluate Materials for Heavy Duty Diesel Fuel Injectors," poster presented at the *2003 International Conference on Wear of Materials*, Washington, D.C., March 31–April 3, 2003.