Friction and Wear Enhancement of Titanium Alloy Engine Components

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Overview

Timeline

- Project start date: October 2009
- Project end date: September 2011
- Percent complete: 12%

Budget

- Total project funding: DOE 100%
- Funding for FY10: $350K ($256K rec’d to-date)
- Funding for FY11: $350K
- Funding for FY12: $350K

Barriers

Barriers addressed:
- Engine weight detracts from vehicle freight efficiency.
- High Efficiency Clean Combustion (HFCC) increases strength reqm’ts
- Ti alloys ~43% lighter than steel but have friction and wear issues.

Partners

- Informal collaboration with Cummins Engine Co., Inc.
- Greenleaf Corp., NASA GRC
- Project lead: ORNL
Relevance to OVT Goals

- Addresses the goal of **50% improvement in freight efficiency** (ton-miles/gallon) by substituting strong, durable, corrosion-resistant alloys for steel components.

- Enable increased use of titanium alloys in friction- and wear-critical engine components like:
  - Connecting rods (end brgs)
  - Pistons (wrist pin and skirt area)
  - Valves
  - Valve guides
  - Movable vanes in turbochargers
  - Bushings in EGR systems

- Compared to other light metals, like Al and Mg, Ti alloys offer outstanding corrosion resistance, high specific strength and stiffness, and decades of aerospace technology to leverage their development.

- Development of lower-cost Ti raw materials (e.g. powders) in recent years expands the possibilities to use Ti for engine components.
Objectives

FY 2010 Objectives:

- **System definition**: To define the connecting rod bearing operating conditions and to understand the requirements for engineered bearing surfaces for that application.

- **Select Candidate Materials and Treatments**: Based on prior work, consultation with partners, and a literature review, select candidate surface treatments and coatings for Ti-6Al-4V alloy for initial friction and wear evaluation. Both commercial and experimental treatments and surface texturing methods will be considered.

- **Complete Bench-Scale Pre-Screening Tests**: Complete preliminary friction and wear tests of selected surface treatments and coatings, and down-select promising materials for further testing in the simulator to be built.

- **Complete Design and Construction of a Spectrum Loading Test Rig**: Engine bearings experience variable, non-steady-state loadings. Based on the problem definition (above), design a programmable loading spectrum test system.
## Milestones for FY 2010

<table>
<thead>
<tr>
<th>Month / Year</th>
<th>Milestone</th>
</tr>
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<tbody>
<tr>
<td><strong>Sep / 2010</strong></td>
<td><strong>Select candidate surface engineering approaches and conduct bench tests:</strong> Investigate prior approaches to improving Ti load-bearing surfaces, select most promising methods, and conduct bench tests on bare and treated surfaces to down-select approaches for evaluation during Phase II.</td>
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<td><strong>Sep / 2010</strong></td>
<td><strong>Design a variable load, large-end bearing simulator for use in Phase II:</strong> Design and build a rotating test.rig capable of applying a spectrum load on test specimens designed to simulate conditions in connecting rod bearings and other variable loaded contact surfaces.</td>
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Bearing surfaces in a connecting rod

Small end bearing – piston end (oscillating, high load, low speed)

Criteria for plain bearings:

- Maximum load carrying capacity
- Maximum permissible wear
- Maximum operating temperature
- Effect of lubricant loss (‘starvation’)

Current insert materials are relatively soft:

- Al-Sn, Al-Sn-Cu, Al-Sn-Ni-Cu, Sn-Al, Al-Si, Cu-based, and multi-layered

Big end bearing – crank shaft end (rotating, high load, medium, speed)
Due to engine dynamics, bearings operate under a spectrum of loads

- **Causes**: inertia of the rotating shaft, periodic combustion events, engine dynamics
- **Effects**: Varying normal force, changing oil film thickness, and changing lubrication regime within each rotation cycle.

*Forces on a big end bearing (data from a polar load diagram)*
Friction and wear are only two bearing material requirements...

- LOW FRICTION
- CONFORMABILITY
- EMBEDABILITY
- WEAR RESISTANCE
- HEAT TOLERANCE
- SEIZURE RESISTANCE
- CORROSION RESISTANCE

Availability and Cost (including the cost of changing to a different material)
Titanium alloys offer lightweight and corrosion resistance

<table>
<thead>
<tr>
<th>Property</th>
<th>Carbon steel</th>
<th>Al alloys (typ.)</th>
<th>Mg alloys (typ.)</th>
<th>Ti-6Al-4V (typ.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>7.8</td>
<td>2.8</td>
<td>1.74</td>
<td>4.43</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>200.</td>
<td>70.</td>
<td>45.</td>
<td>112.</td>
</tr>
<tr>
<td>Specific strength*</td>
<td>45. – 60.</td>
<td>35. – 125.</td>
<td>130.</td>
<td>200 - 250.</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Pitting, general corrosion, scaling problems</td>
<td>Stress corrosion, exfoliation, pitting</td>
<td>Galvanic corrosion, attack by road salts</td>
<td>Excellent resist. to road salts, (H-embrittlement)</td>
</tr>
<tr>
<td>Thermal cond. (W/m-K)</td>
<td>42.- 62.</td>
<td>~ 160.</td>
<td>73.</td>
<td>6.83</td>
</tr>
</tbody>
</table>

* Specific strength = Ultimate tensile strength/density

43% lower weight for the same size part
**Approach (Phases I and II Tasks)**

**Phase I**

1. Investigate current state of the art in Ti surface engineering, including aerospace solutions
2. Identify candidate surface engineering methods, prepare simple lab test coupons
3. Test and down-select promising surface engineering approaches

**Phase II**

1. Analyze force, speeds, and operating environments of end bearings on connecting rods
2. Design and build a spectrum loaded, rotary bearing test system
3. Conduct baseline tests on current CR bearing materials

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Year 1
Approach (Phases II and III Tasks)

Year 2

Continue coupon testing on leading candidates from Phase I

Identify most promising surface engineering methods

Conduct spectrum-loaded friction and wear tests on leading candidates / compare to current bearing materials (inserts)

Phase II

Year 3

Identify full-scale testing facilities and dimensions for a prototype conn rod

Prepare one or more prototype Ti conn rods with engineered surfaces

Dynamometer tests at an engine test facility (tbd)

Phase III
Development of a laboratory-scale, ‘spectrum loading’ friction and wear test rig

- Torque measurement
- Shaft angle measurement
- Drip lubrication
- Variable (spectrum) loading capabilities

- Fixtures designed to accommodate both simple shaped specimens or sections cut from connecting rod bearings
Technical Accomplishments and Progress

- **Literature review.** Conducted review of the state-of-the-art in surface treatments and coatings for Ti friction and wear control.

- **Obtained and machined Ti alloys.** Obtained T-6Al-4V alloys, selected testing conditions, machined test coupons, and obtained engine-conditioned diesel oil (SWRI – M11 engine test protocol).

- **Conducted baseline friction and wear tests.** Selected test method (ASTM G133 – Procedures A and B), and conducted first set of reciprocating pin-on-flat tests on non-treated surfaces (baseline).

- **Began initial friction and wear tests of surface treatments.** Began testing oxygen diffusion treated Ti-6Al-4V, IR-formed in situ composites of Ti / TiB2.

- **Ordered first set of hard coatings.** Obtaining magnetron-sputtered coatings (Greenleaf Corp.).

- **Investigating options for patterned (textured) surfaces.** (Virginia Commonwealth University), and **unique alloys** (NASA-GRC).

- **Conducting initial design work on a spectrum-loading test system.**
Technical Progress: Bench-scale testing

ASTM Standard G133 (reciprocating pin on flat developed under DOE/OVT Sponsorship of ORNL)

**Procedure A:** Load = 25 N, 10 mm stroke, 5 cycles/s, 100 m sliding distance, no lubricant, room temperature

**Modified Procedure B:** Load = 200 N, 10 mm stroke, 10 cycle/s, 400 m sliding distance, lubricated,* room temperature

*15W40 engine drain oil, Mack T-11 standard test, 252 hrs, from Southwest Research Institute®, San Antonio, TX
Technical Progress: Initial results (D. Bansal, ORNL)

Dry – no lubricant

- Micro hardness: 3.64 (GPa) HV
- Macro hardness: 37.4 HRC

52100 ball on untreated Ti6Al4V
ASTM G133 proc. A

Used diesel oil

Stopped at COF = 0.32

- 52100 ball on untreated Ti6Al4V
  ASTM G133 proc. B with used oil

Test stopped due to noise and vibration, excessive wear

Micro hardness: 6.98 (GPa) HV
Macro hardness: 35.1 HRC

52100 ball on oxidized Ti6Al4V
ASTM G133 proc. A

COF reduced to ~ 0.08

Non-treated

Treated
Technical Progress: Wear features

Non-treated Ti-6Al-4V not lubricated

- Flat specimen wear
- Ball wear

Non-treated Ti-6Al-4V tested in used diesel oil

- Flat specimen wear
- End of track debris pile-up
- Ball wear
Technical Progress: Initial test results

52100 Ball on Oxidized Ti-6Al-4V: non-lubricated

Wear track on tile
Material pile-up on tile
Wear scar on ball

52100 Ball on Oxidized Ti-6Al-4V: used diesel oil

Wear track on tile
Wear scar on ball
Technical Progress: Initial test results

3-D topographic imaging measurements show differences in wear behavior (ASTM G133 test method)

Wear scar on bare Ti-6Al-4V, slid against an AISI 52100 steel ball with no lubrication for 1000 seconds (100 m sliding distance).

Wear scar on bare Ti-6Al-4V in used diesel oil: Terminated after 90 seconds due to excessive vibration.
Collaboration and Coordination with Other Institutions

- **Cummins Engine Co., Inc.** (Columbus, IN) – discussions and advice on applications for Ti in diesel engine components,
- **Greenleaf Corporation** (Sagertown, PA) – is providing several types of hard coatings on Ti test coupons supplied by ORNL,
- **Virginia Commonwealth University**, Center for Precision Forming (Richmond, VA) – collaboration on exploratory methods for surface texturing of Ti alloy bearing surfaces,
- **NASA, Glenn Research Center** (Cleveland, OH) – Exploring a novel Ti-based intermetallic alloy for a possible surface alloying approach.
Proposed Future Work

Remainder of FY 2010:

- Continue bench-scale friction and wear tests of potential bearing surface treatments.
- Down-select promising approaches to friction and wear improvement.
- Design, build, and test a spectrum loading wear test system.

FY 2011:

- Spectrum load testing of the leading bearing candidates.
- Confirm plans for scale up of the concept validation in year 3.
Summary

• If surface properties and component costs can be improved, new applications for lightweight Ti alloys in energy-efficient engines become feasible.

• The current project is focused on integral big end and small end bearings for connecting rods to reduce weight and eliminate the need for additional inserts.

• A literature review, coupled by past OVT-sponsored ORNL tribology work, is being used to down-select candidate surface treatments and coatings. Initial results demonstrate the effects of surface treatment on the friction and wear of Ti in engine-conditioned diesel oil.

• In parallel with initial laboratory-scale screening tests of bare, treated, and coated Ti coupons, a spectrum loaded bearing materials test system is being designed and developed.

• Work in the coming years will exploit the use of multiple methods to engineer durable, low-friction Ti bearing surfaces for lightweight diesel engine components.