# Friction and Wear Enhancement of Titanium Alloy Engine Components


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**Project ID: pm007**

U.S. DEPARTMENT OF ENERGY



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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

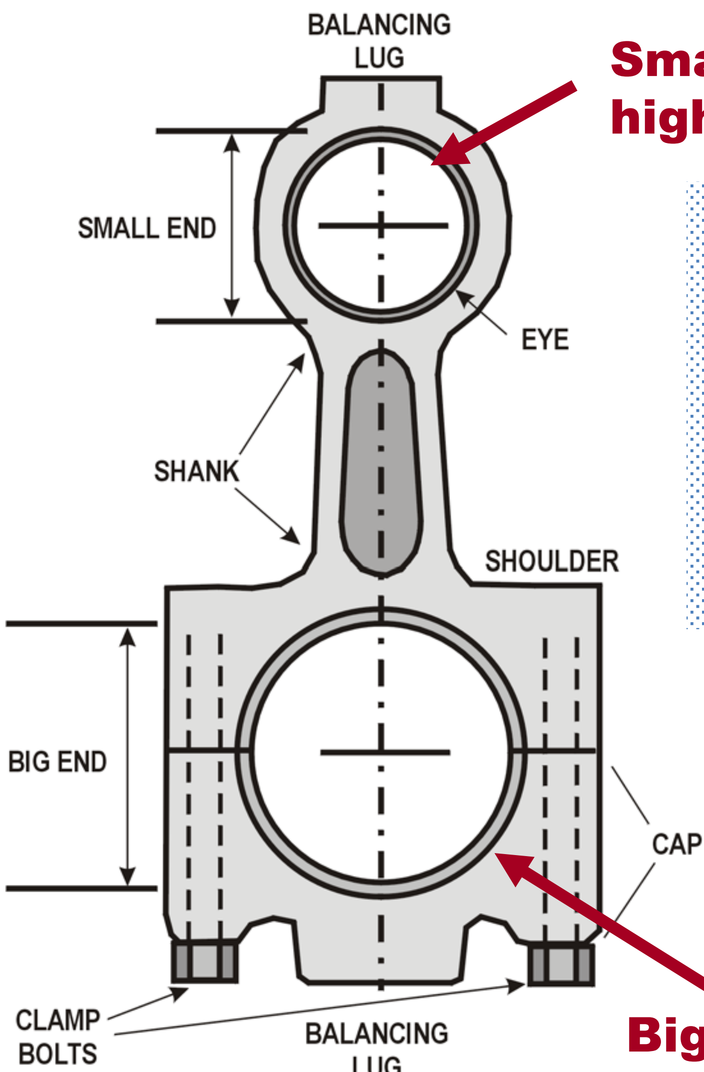
## FY 2010 Objectives:

- **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

| Month / Year | Milestone |
| --- | --- |
| Sep / 2010 | **Select candidate surface engineering approaches and conduct bench tests**: 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. |
| Sep / 2010 | **Design a variable load, large-end bearing simulator for use in Phase II**: 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. |

# 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)**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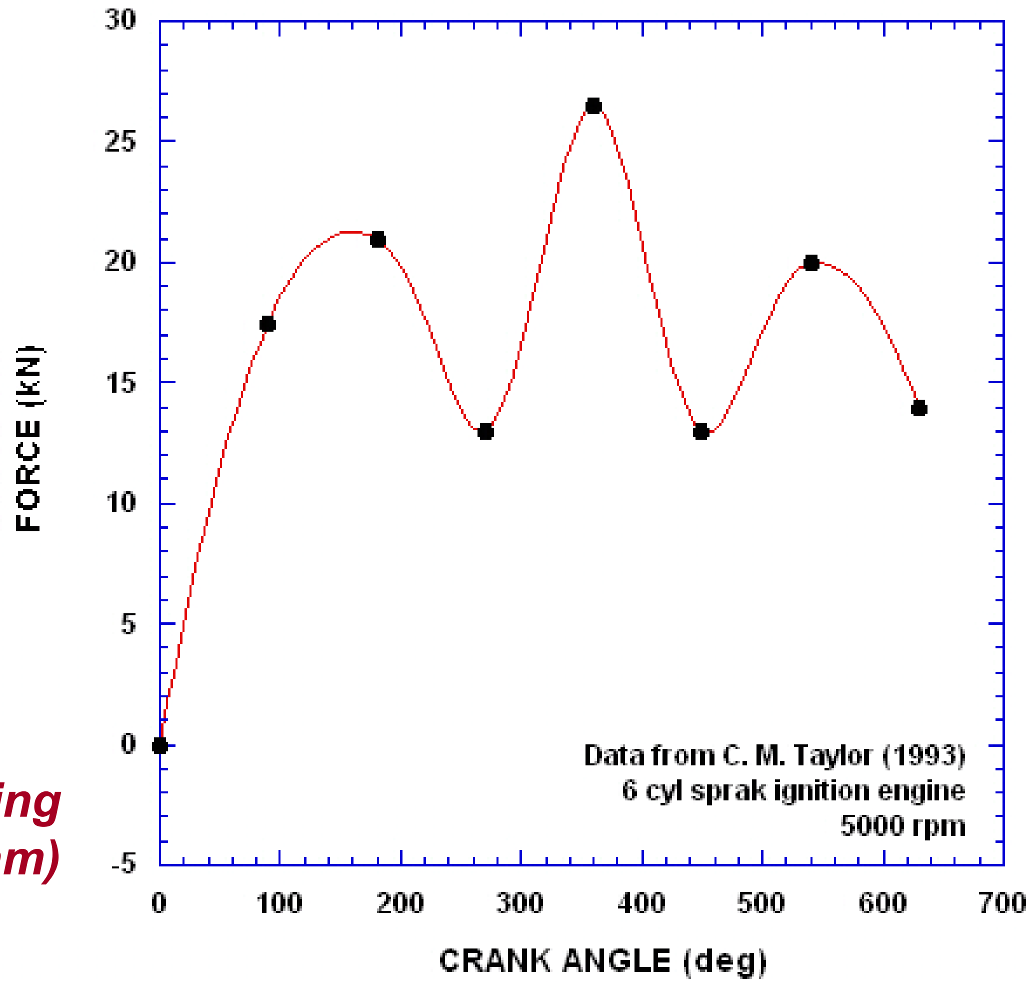
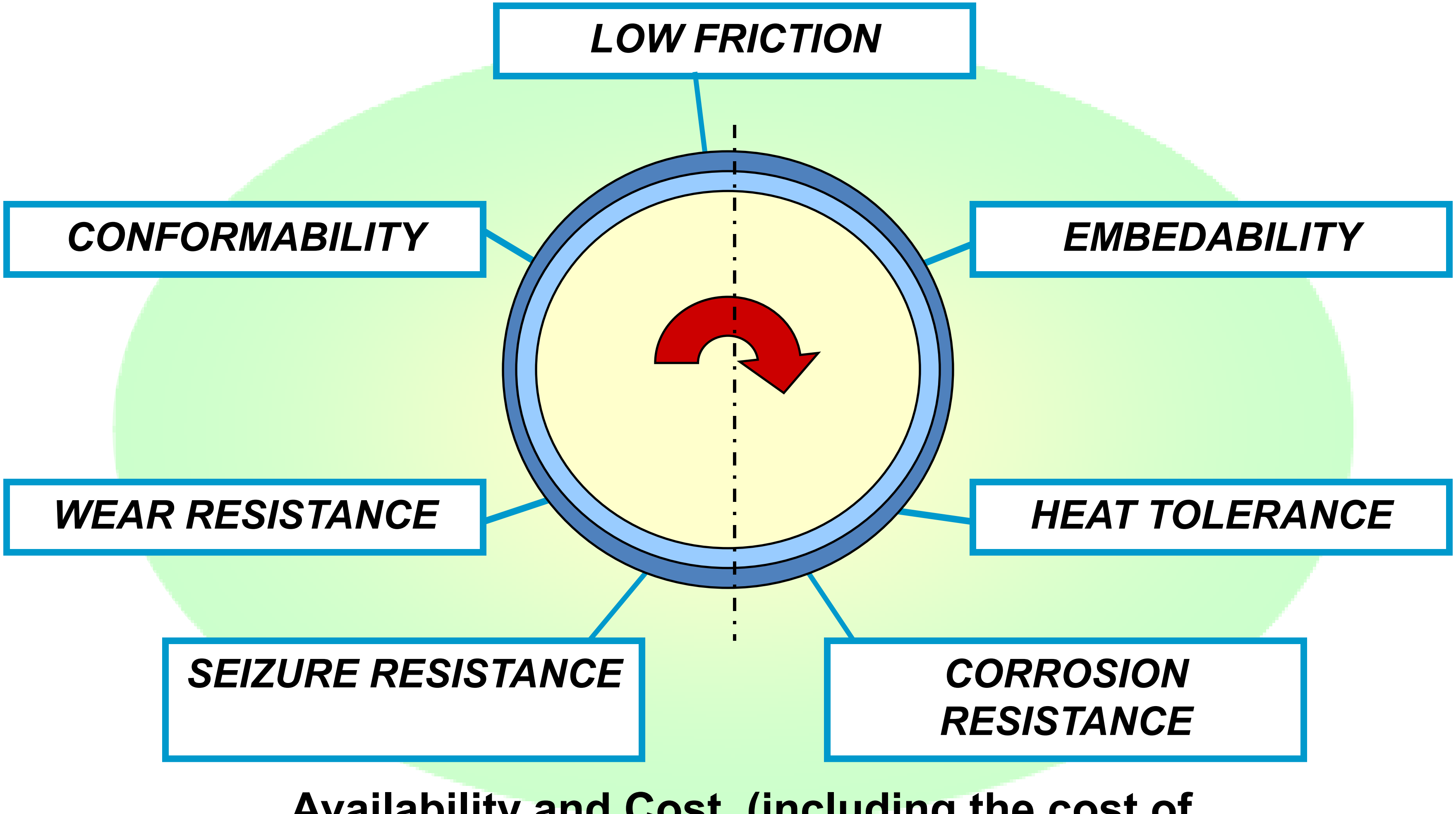
# Due to engine dynamics, bearings operate under a spectrum of loads

- **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…




**Availability and Cost (including the cost of changing to a different material)**

# Titanium alloys offer lightweight and corrosion resistance

***43% lower weight for the same size part***

| Property | Carbon steel | Al alloys (typ.) | Mg alloys (typ.) | Ti-6Al-4V (typ.) |
|---|---|---|---|---|
| Density ($g/cm^3$) | 7.8 | 2.8 | 1.74 | 4.43 |
| Elastic modulus (GPa) | 200. | 70. | 45. | 112. |
| Specific strength* | 45. – 60. | 35. – 125. | 130. | 200 - 250. |
| Corrosion | Pitting, general corrosion, scaling problems | Stress corrosion, exfoliation, pitting | Galvanic corrosion, attack by road salts | Excellent resist. to road salts, (H-embrittlement) |
| Thermal cond. (W/m-K) | 42.- 62. | ~ 160. | 73. | 6.83 |

* Specific strength = Ultimate tensile strength/density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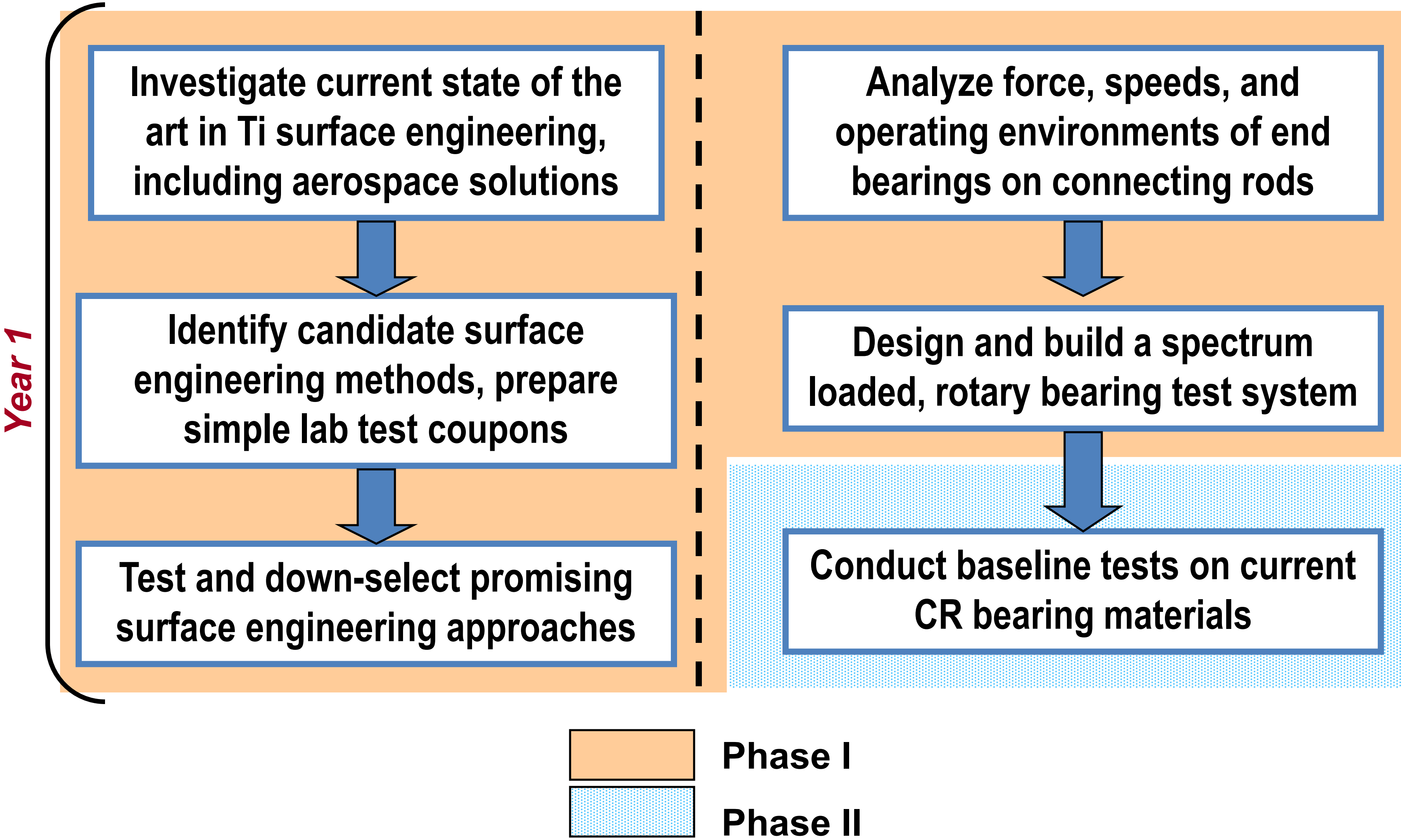
# Approach (Phases I and II Tasks)



# Approach (Phases II and III Tasks)

**Year 2** (Phase II)

- 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)

***SCALE-UP and VALIDATION***

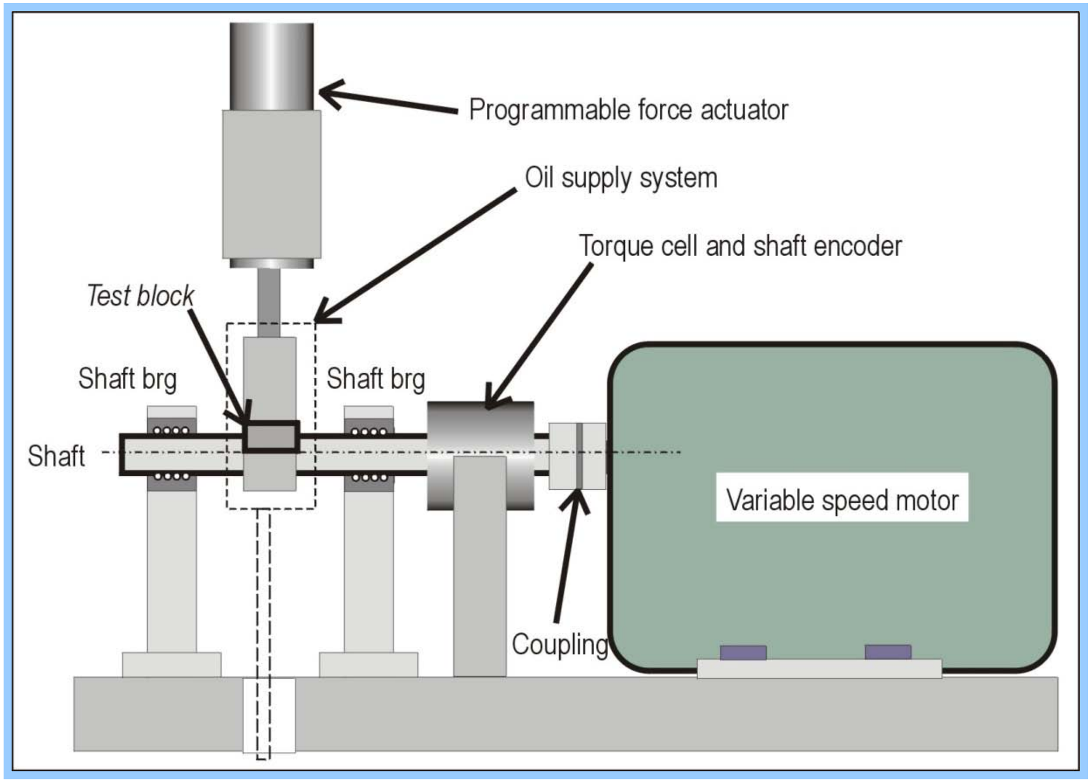
**Year 3** (Phase III)

- 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 II**

**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

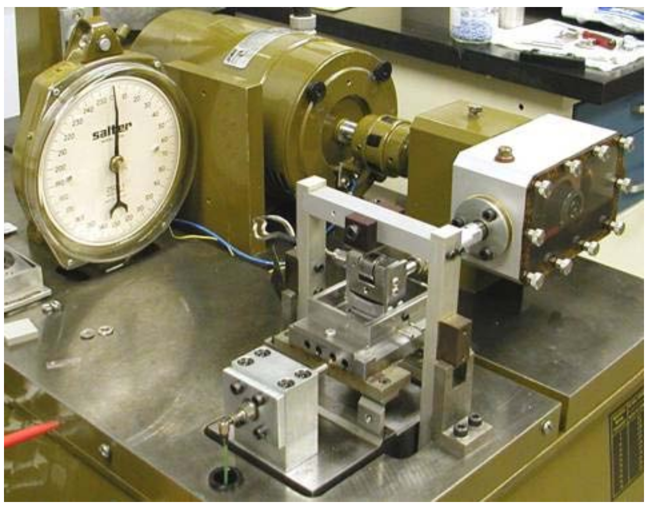
- **Literature review**. Conducted review of the state-of-the-art in surface treatments and coatings for Ti friction and wear control
- **Obtained and machined Ti alloys**. Obtained T-6Al-4V alloys, selected testing conditions, machined test coupons, and obtained engine-conditioned diesel oil (SWRI – 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 / $TiB_2$.
- **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**.

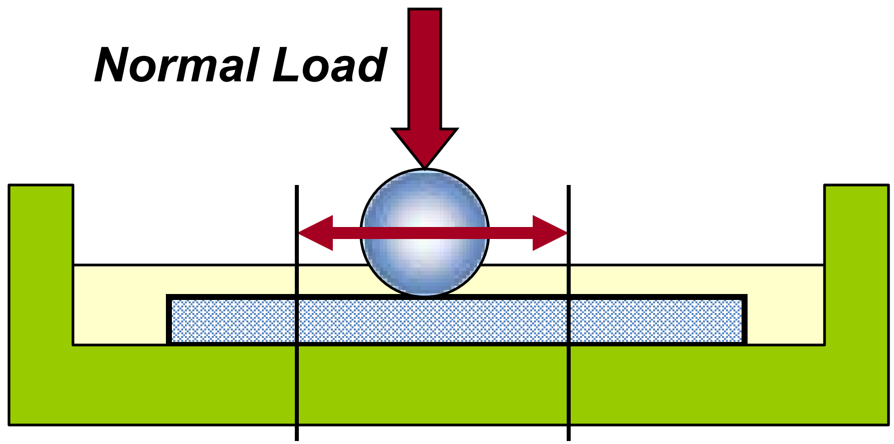
# Technical Progress: Bench-scale testing

**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



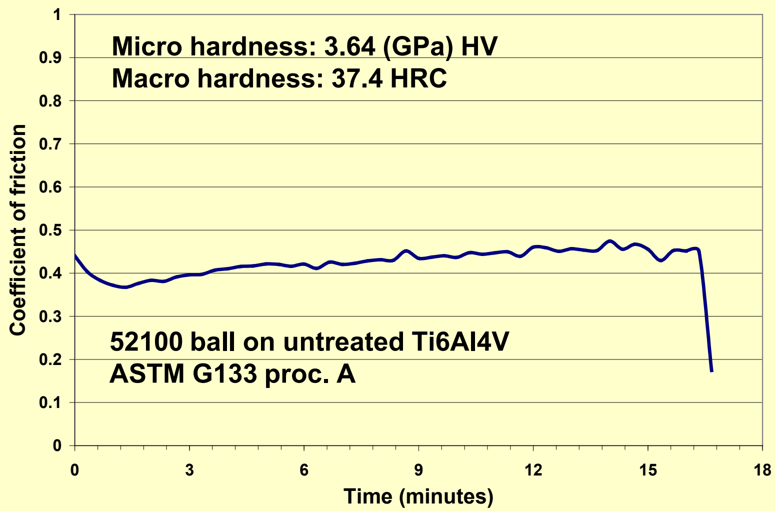

***15W40 engine drain oil, Mack T-11 standard test, 252 hrs, from Southwest Research Institute®, San Antonio, TX**

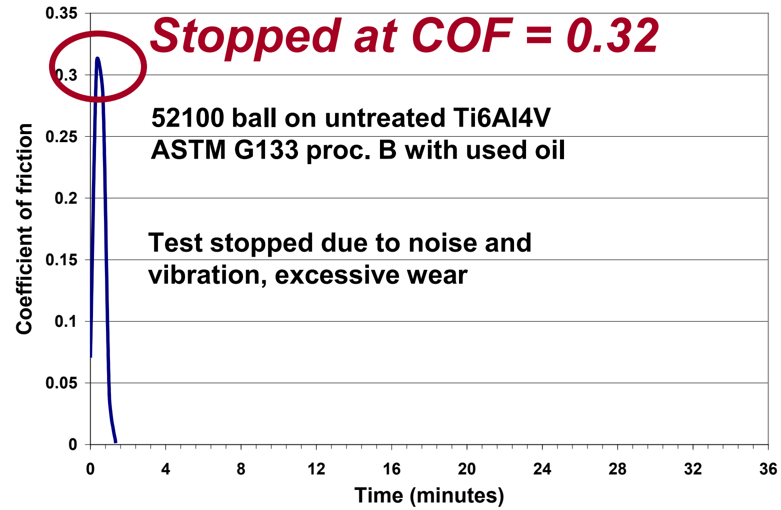
# Technical Progress: Initial results (D. Bansal, ORNL)

*Dry – no lubricant*

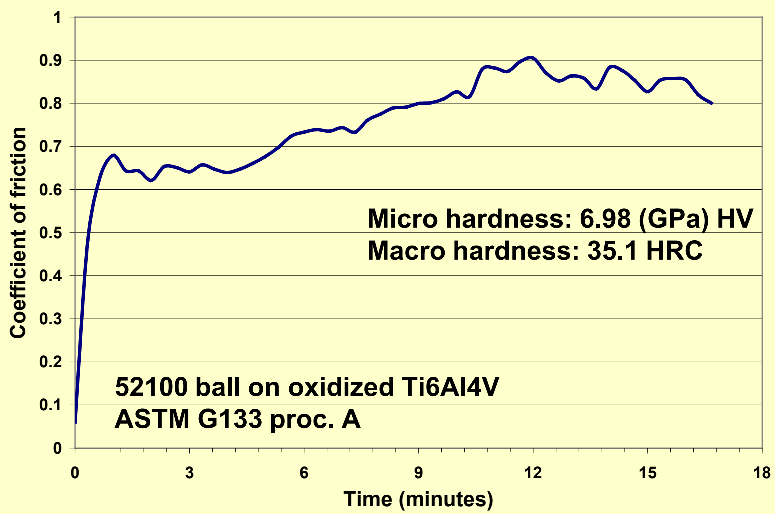
*Used diesel oil*

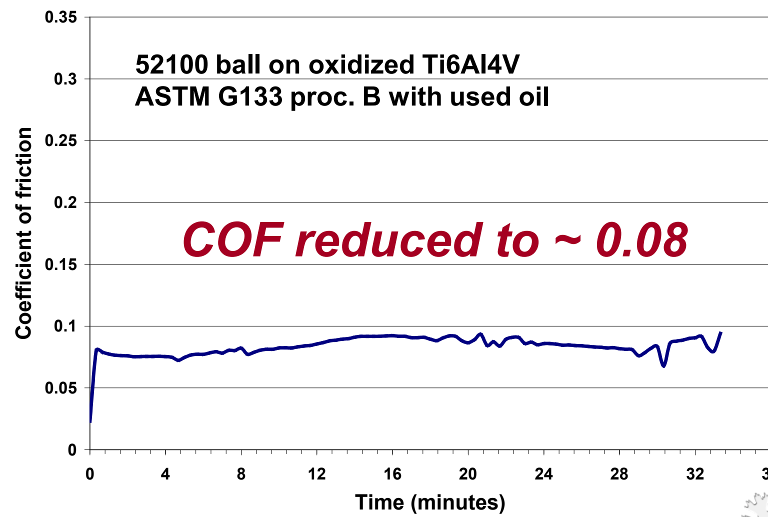
*Non-treated*



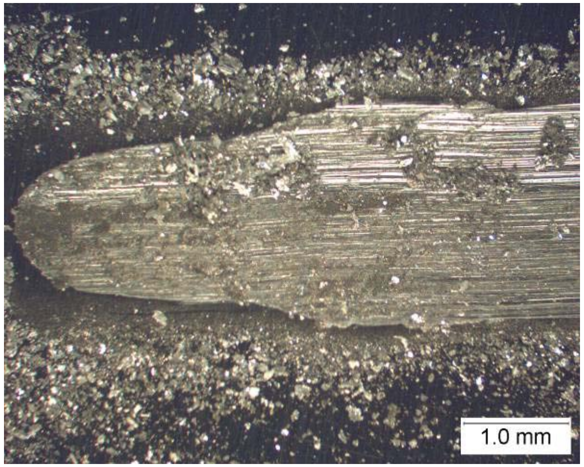

*Treated*



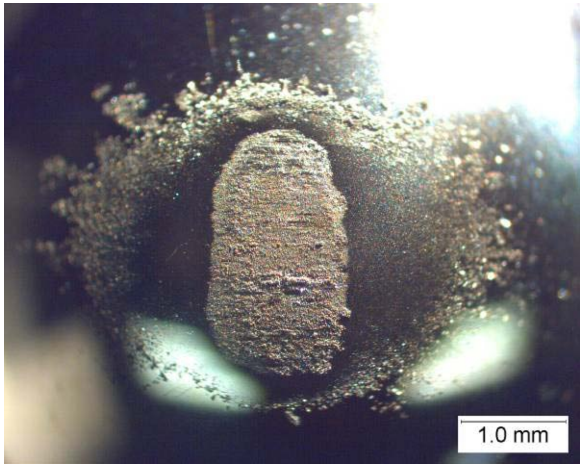



# Technical Progress: Wear features

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

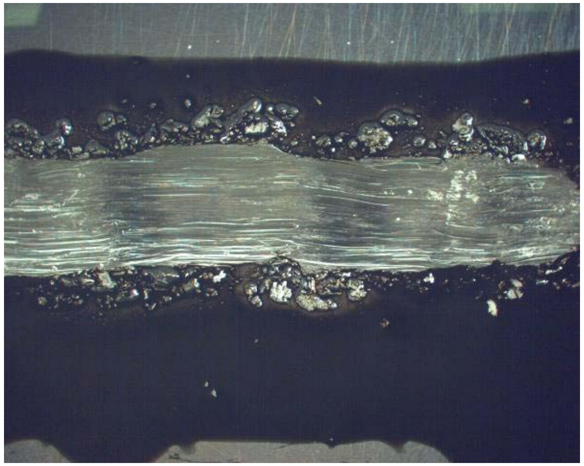



Flat specimen wear

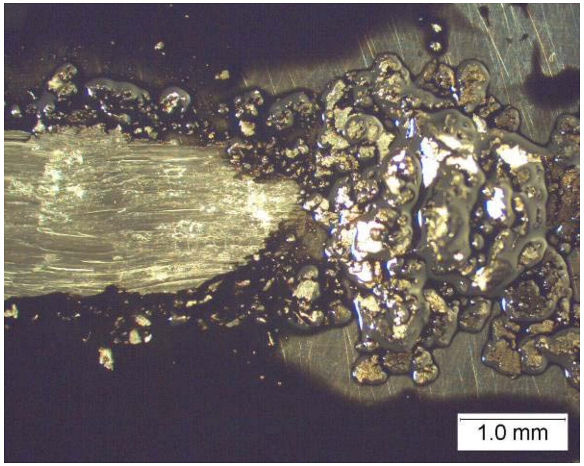



Ball wear

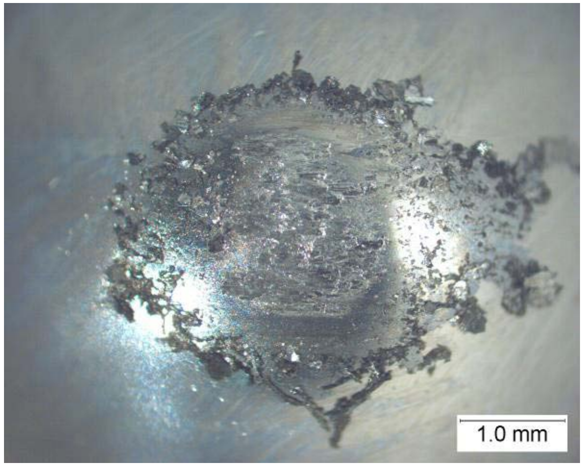
## Non-treated Ti-6Al-4V *tested in used diesel oil*



Flat specimen wear



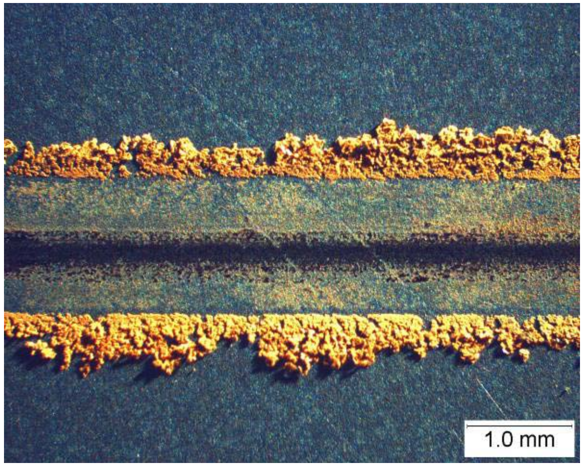

End of track debris pile-up



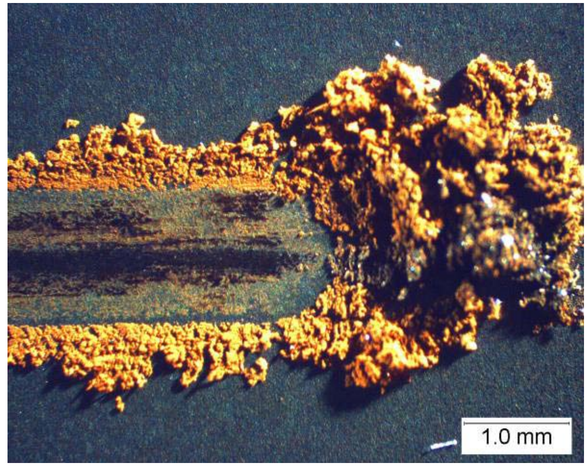

Ball wear

# Technical Progress:  Initial test results

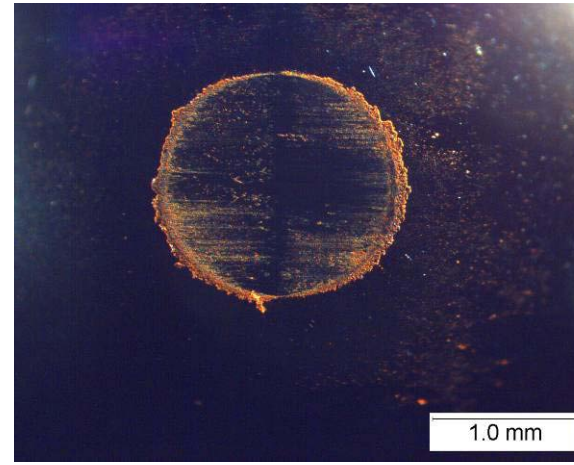
## 52100 Ball on Oxidized Ti-6Al-4V: *non-lubricated*




Wear track on tile

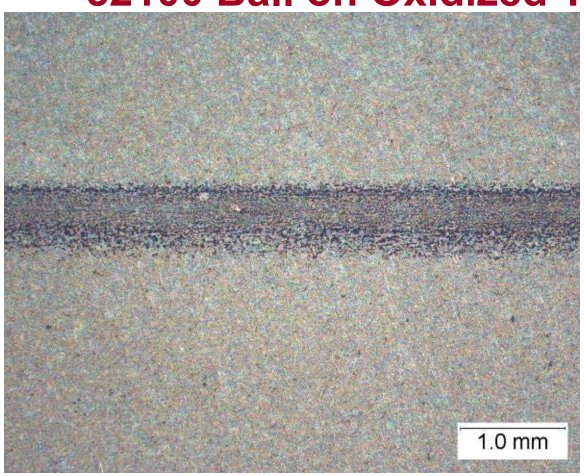



Material pile-up on tile

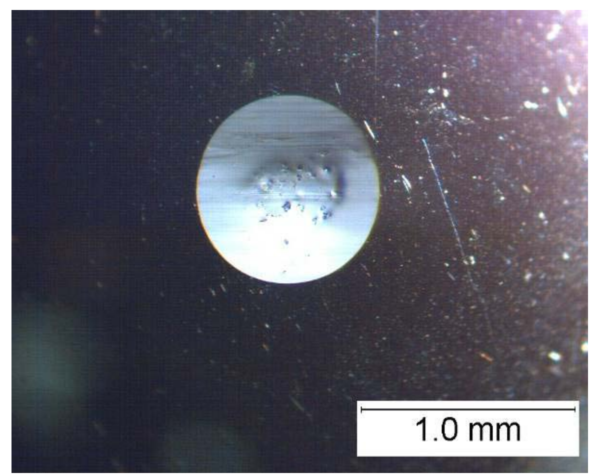



Wear scar on ball

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



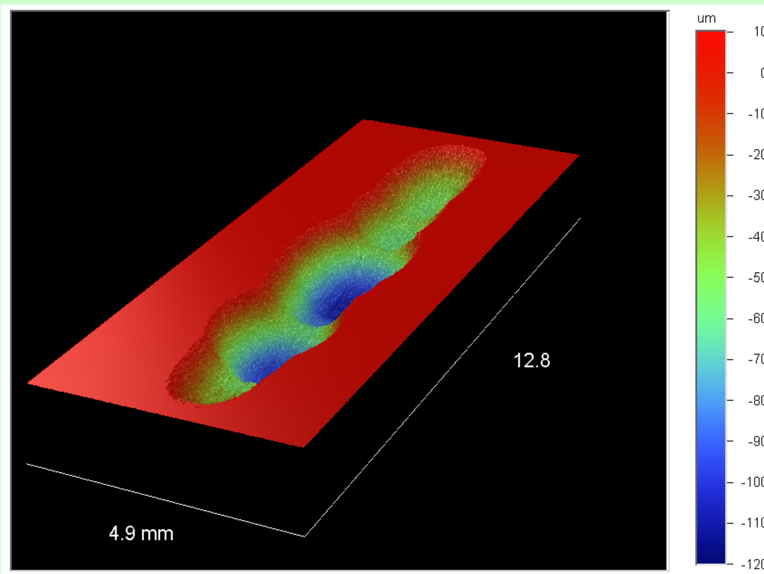

Wear track on tile



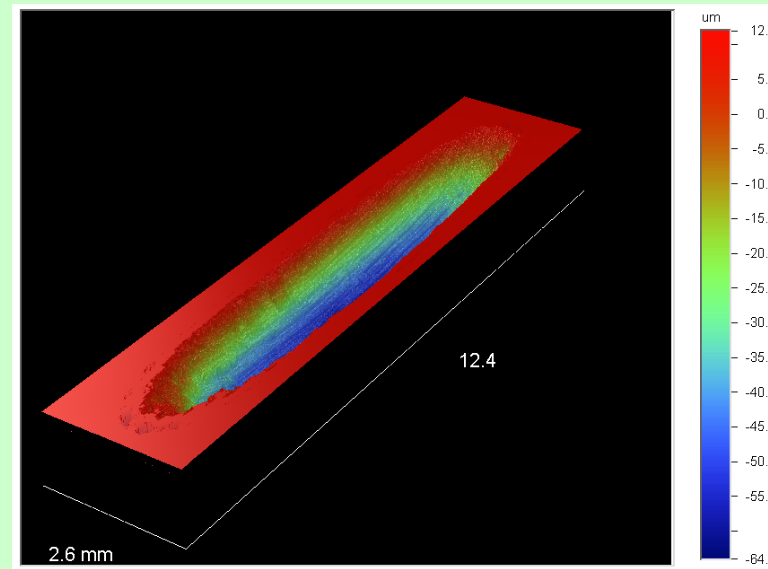

Wear scar on ball

# 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.**