Friction and Wear Enhancement of Titanium Alloy Engine Components

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Project ID: pm007_Blau

U.S. DEPARTMENT OF
ENERGY

Overview

Timeline

- Project start date: October 2009
- Project end date: September 2011
- Percent complete: 67%

Budget

Total project funding: DOE 100%

- Funding for FY10: $ 274 K
- Funding for FY11: $ 150 K
- Funding for FY12: (pending)

Barriers

Barriers addressed:

- Light-weighting components to improve heavy truck engine thermal efficiency to 50% by 2015.
- High Efficiency Clean Combustion (HFCC) increases strength reqm'ts
- Ti alloys ~43% lighter than steel but have friction and wear challenges.

Partners

- NDA with Cummins Engine Co.
- Informal collaborations: surface treatment/coatings developers
- 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 and valve guides	Crankshafts
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 2011 Objectives:

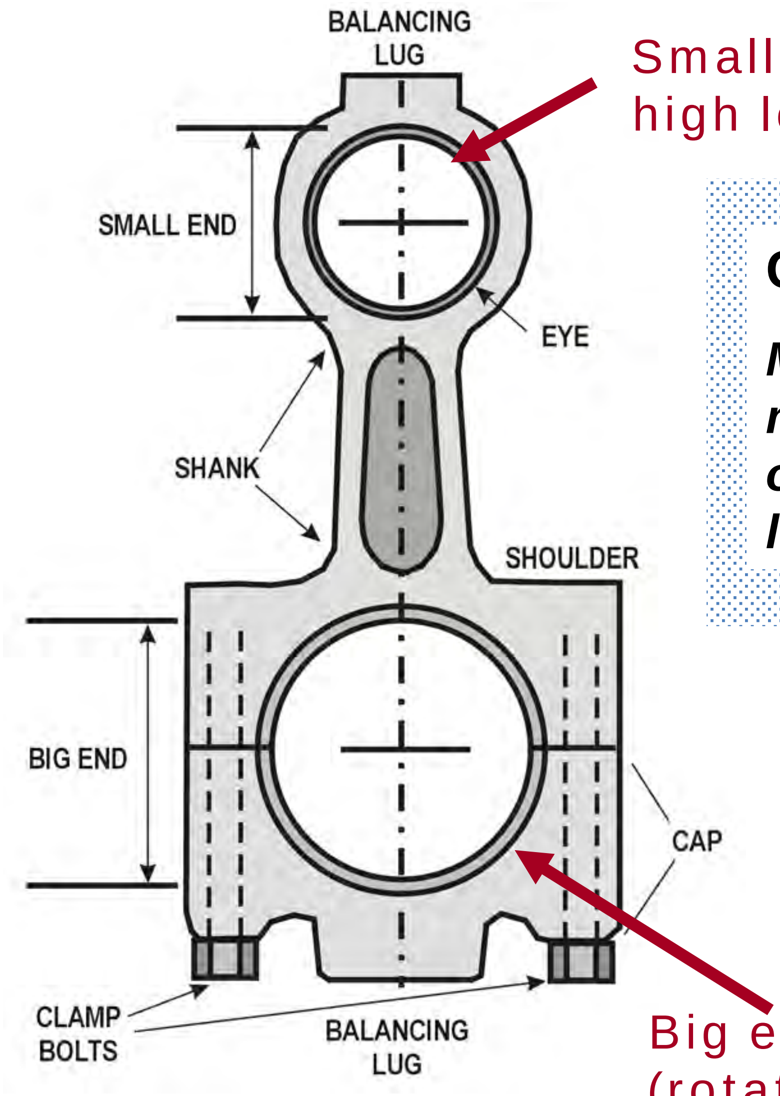
- **Complete Friction and Wear Studies of Coatings and Treatments that passed Screening Tests in FY 2010:** Conduct in-depth investigation of commercial and experimental surface engineering treatments that passed pre-screening tests in FY 2010.* Understand why treatments and coatings performed as they did as a basis for further optimization.
- **Complete Construction of a Variable-Load Bearing Test (VLBT) Rig and Investigate Down-Selected Coatings and Surface Treatments:** Engine bearings experience variable, non-steady-state loadings which can cause intermittent wear and periodic loss of lubricating films. Based on a tribosystem analysis for connecting rods and advice from an OEM, the programmable VLBT system will be used to find the best surface engineering treatments for Ti alloys.
- **Identify a Commercial Diesel Engine Connecting Rod** as a candidate for replacement with surface engineered Ti –based version.

* presented at the *International Conference on Wear of Materials*, Philadelphia PA (April 3-7, 2011).

Milestones for FY 2011

Month / Year	Milestone
March / 2011	Complete construction, instrumentation, and baseline tests of a variable-load large-end bearing testing system (VLBT): Complete machining and assembly, installation of sensors and computerized load controls. Verify operating performance. Conduct baseline tests on non-treated Ti alloy and bearing bronze against a hardened steel counterface (surrogate for the crankshaft material),
Sep / 2011	Complete VLBT tests of down-selected surface engineering treatments and coatings for Ti: Compare VLBT baseline lubricated friction and wear test results with those for promising surface treatments and coatings that passed Phase 1 screening in FY 2010.

Bearing surfaces in a connecting rod



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

Criteria for plain bearings:

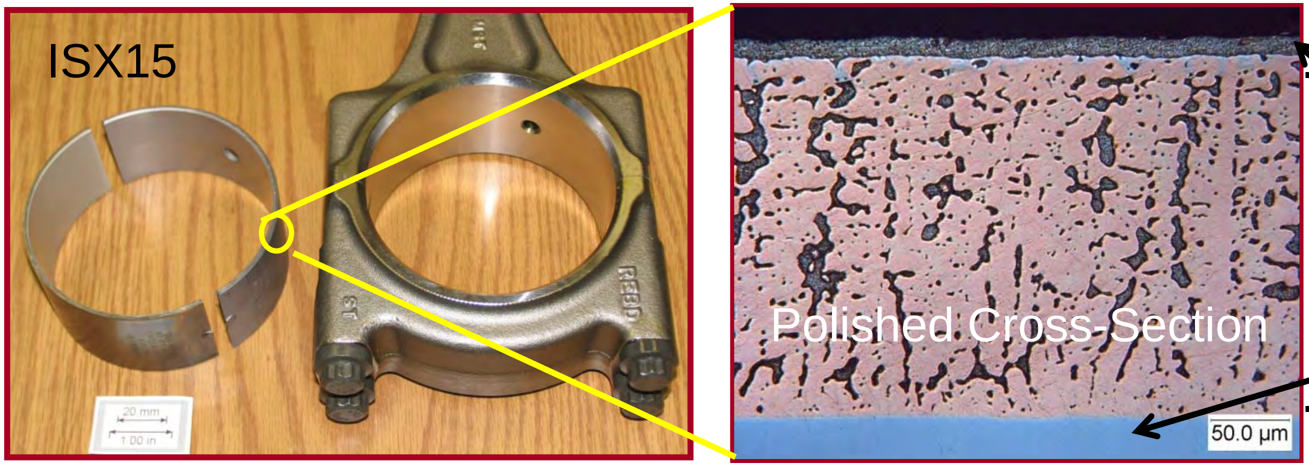
Maximum load carrying capacity, maximum permissible wear, maximum operating temperature, effect of lubricant loss ('starvation')

Current insert materials are relatively soft and some contain Pb:

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)

Large-end 'tri-metal' bearing inserts in a typical HDD engine connecting rod



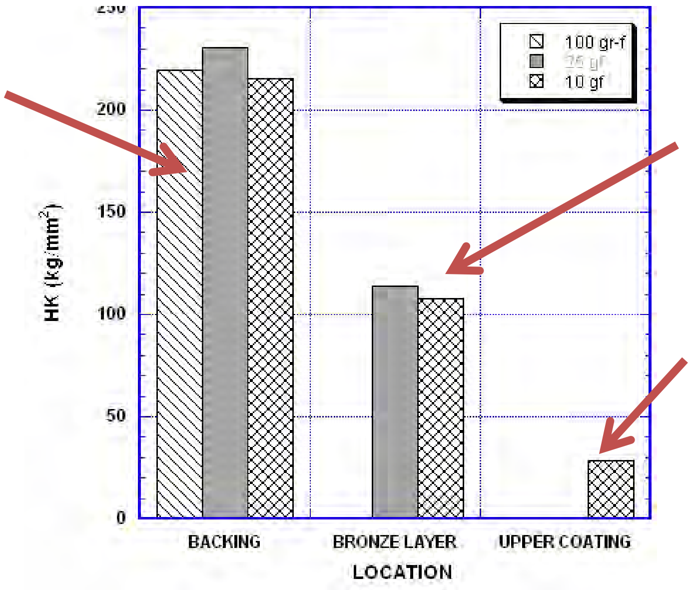
Solid lubricant layer

Bronze alloy layer (Pb, Sn, In)

Steel back plate

Indentation testing reveals insert layer functionality

Back plate provides stiffness and strength



Bronze layer imparts embedability and solid lubrication during start-up and boundary lubrication

Soft upper layer provides conformability and lubrication during wear-in

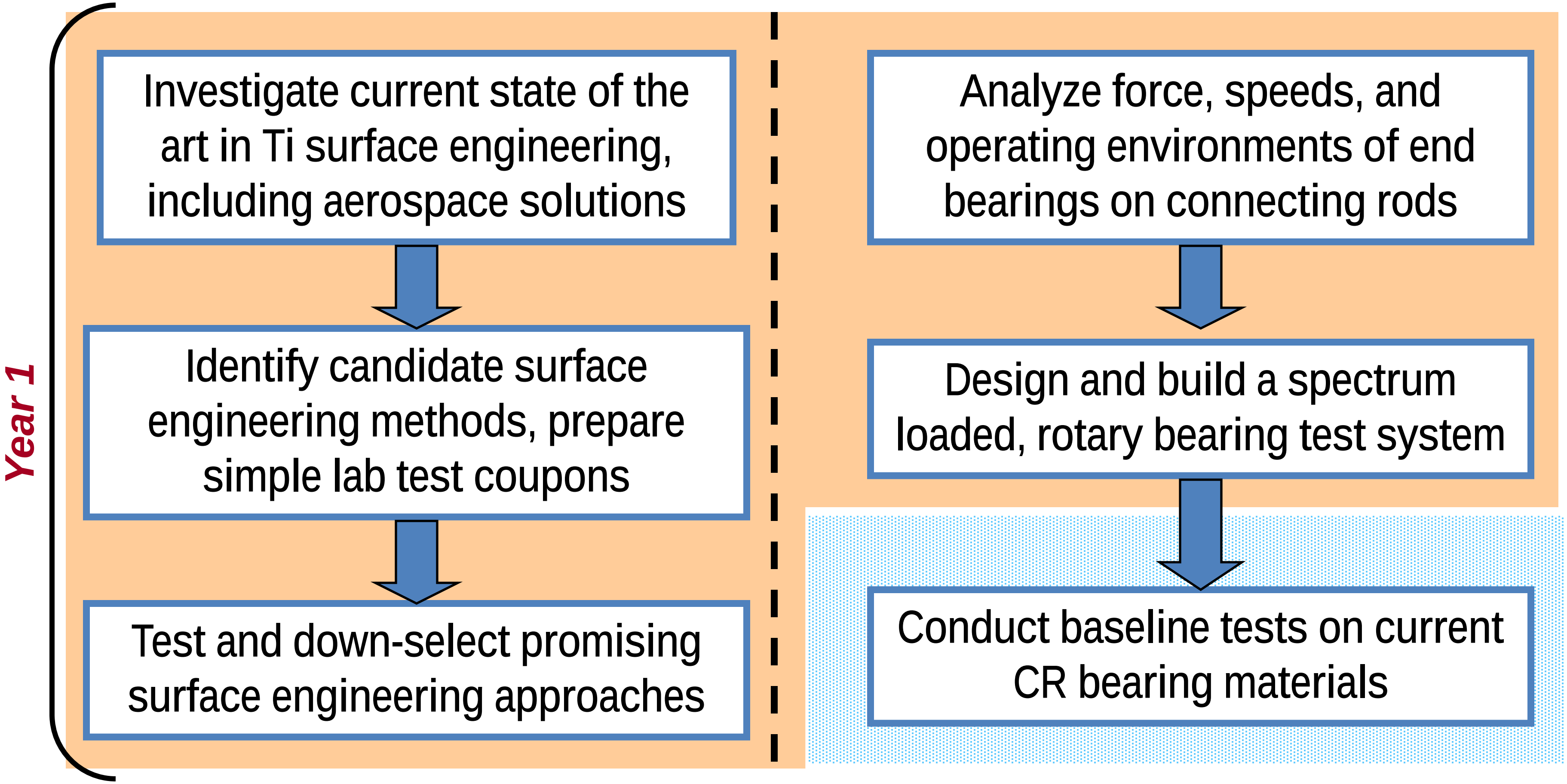
Why Ti?

- **Lightweight and corrosion-resistant**
- **Metallurgy well-studied (aerospace)**
- **New, more cost-effectibe processing technologies being developed**
- **43% lower weight for the same sized 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, aqu. corrosion
Thermal cond. (W/m-K)	42.- 62.	~ 160.	73.	6.83

* Specific strength = Ultimate tensile strength/density

Approach (Phases I and II Tasks)



Investigate current state of the art in Ti surface engineering, including aerospace solutions

Identify candidate surface engineering methods, prepare simple lab test coupons

Test and down-select promising surface engineering approaches

Analyze force, speeds, and operating environments of end bearings on connecting rods

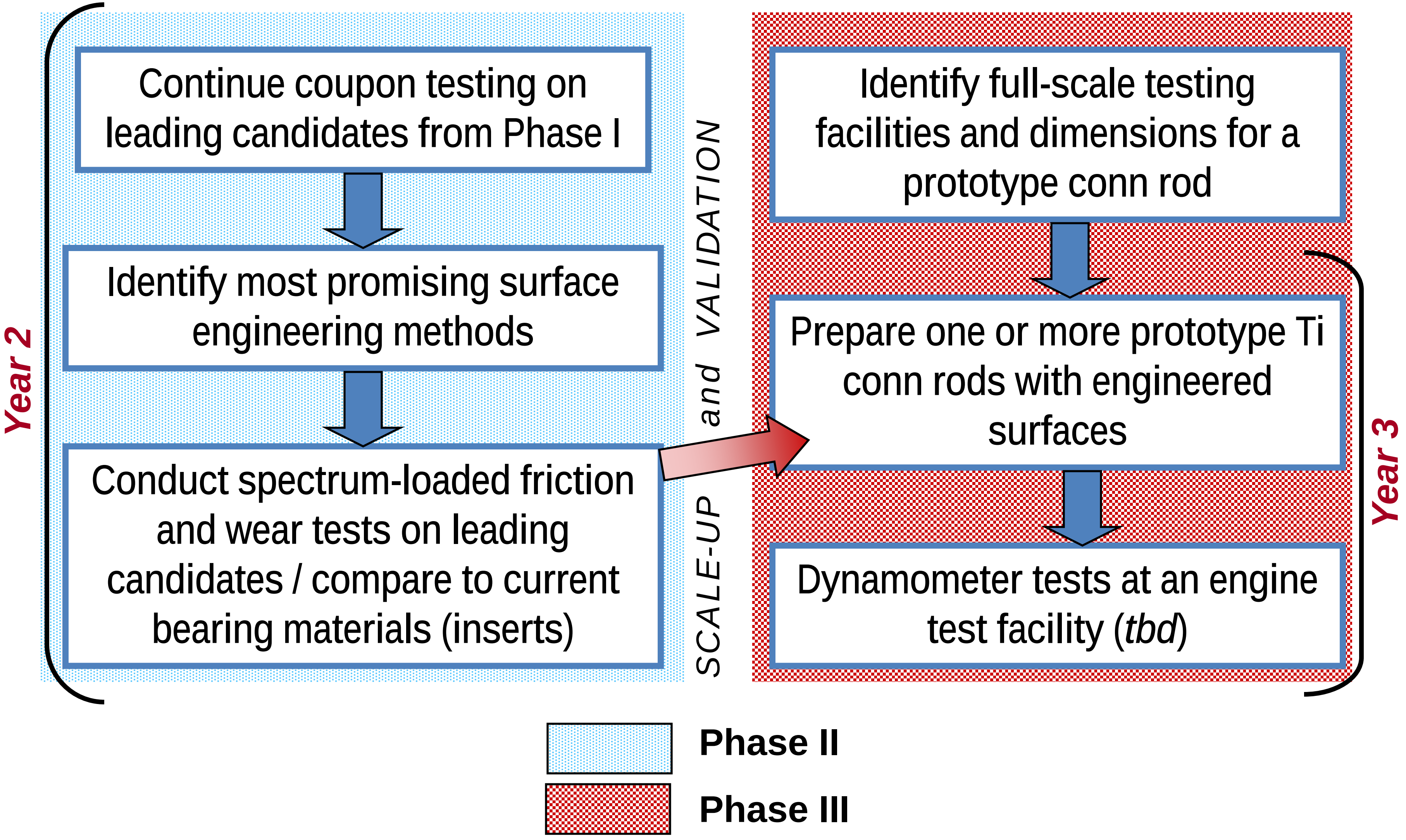
Design and build a spectrum loaded, rotary bearing test system

Conduct baseline tests on current CR bearing materials

🟧 **Phase I**

▨ **Phase II**

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)

SCALE-UP and VALIDATION

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*)

Year 3

▨ **Phase II**

▨ **Phase III**

21 Materials, Treatments and Coatings Were Considered and Evaluated in FY 2010 using Bench-Scale Tests

Bronze reference
Novel NASA alloy

ORNL developed OD

Treated NASA alloy

Commercial coatings

ANL diamond film
Nanocoating (from a DOE/ITP project)

IR Ti composite from ORNL/LDRD

	BULK MATERIALS
1	Baseline, non-treated Ti-6Al-4V
2	Pb-Sn bronze alloy CDA 932 (baseline bearing bronze)*
3	60Ni-40Ti (a NASA development)**
	MECHANICAL TREATMENTS
4	Shot peening*
5	Low plasticity burnishing*
	THERMAL and CHEMICAL TREATMENTS
6	Oxygen diffusion treatment (developed by J. Qu at ORNL)**
7	Carburizing*
8	Nitriding*
9	Surface alloying to form 60Ni-Ti (pending results of tests on bulk 60Ni-40Ti, line 3)
10	Electrochemical anodizing*
	HARD and SOFT COATINGS
11	TiN hard coating*
12	CrN hard coating*
13	DLC hard coating ***
14	Nanocomposite AlMgB (developed under a DOE/ITP project)****
15	In situ IR-produced Ti MMC (developed at ORNL under Laboratory Directed R&D funding)**
16	Metallic soft coating of Cu-Ni-In on Ti-6Al-4V*
17	Metallic soft coating of Cu-Ni-In on CDA 932 bronze*
	HYBRID TREATMENTS
18	Shot peening* after oxygen diffusion treatment**
19	Shot peening* after carburizing*
20	Shot peening* after nitriding*
21	Cu-Ni-In soft coating* after shot peening*

Both commercial and experimental treatments were pre-screened in Phase I

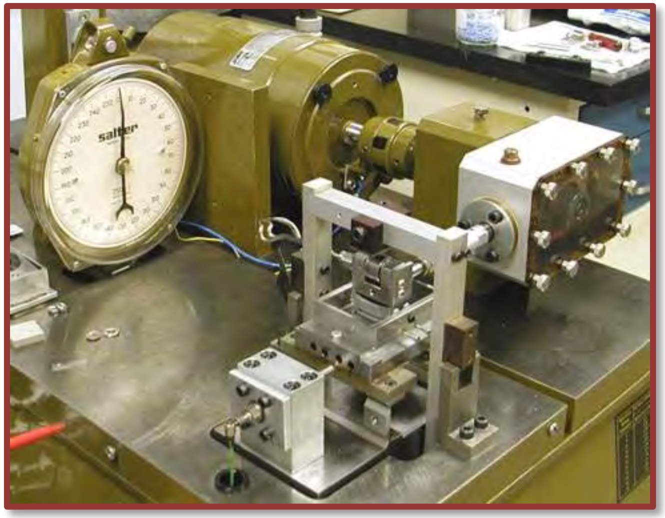
** Commercial source,* *** Produced at ORNL*
**** Produced at ANL* ***** Produced at a company R&D Lab*

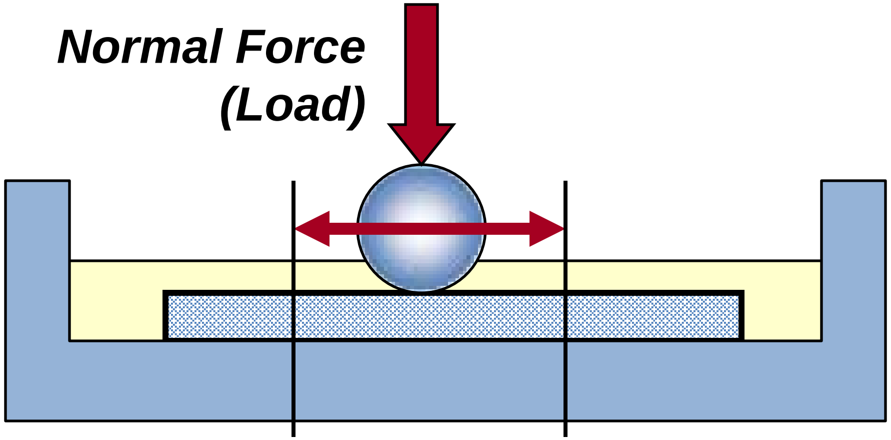
Technical Progress: Phase I Screening (FY2010)

ASTM Standard G133 (reciprocating pin-on-flat standard developed by ORNL under DOE/OVT sponsorship)

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

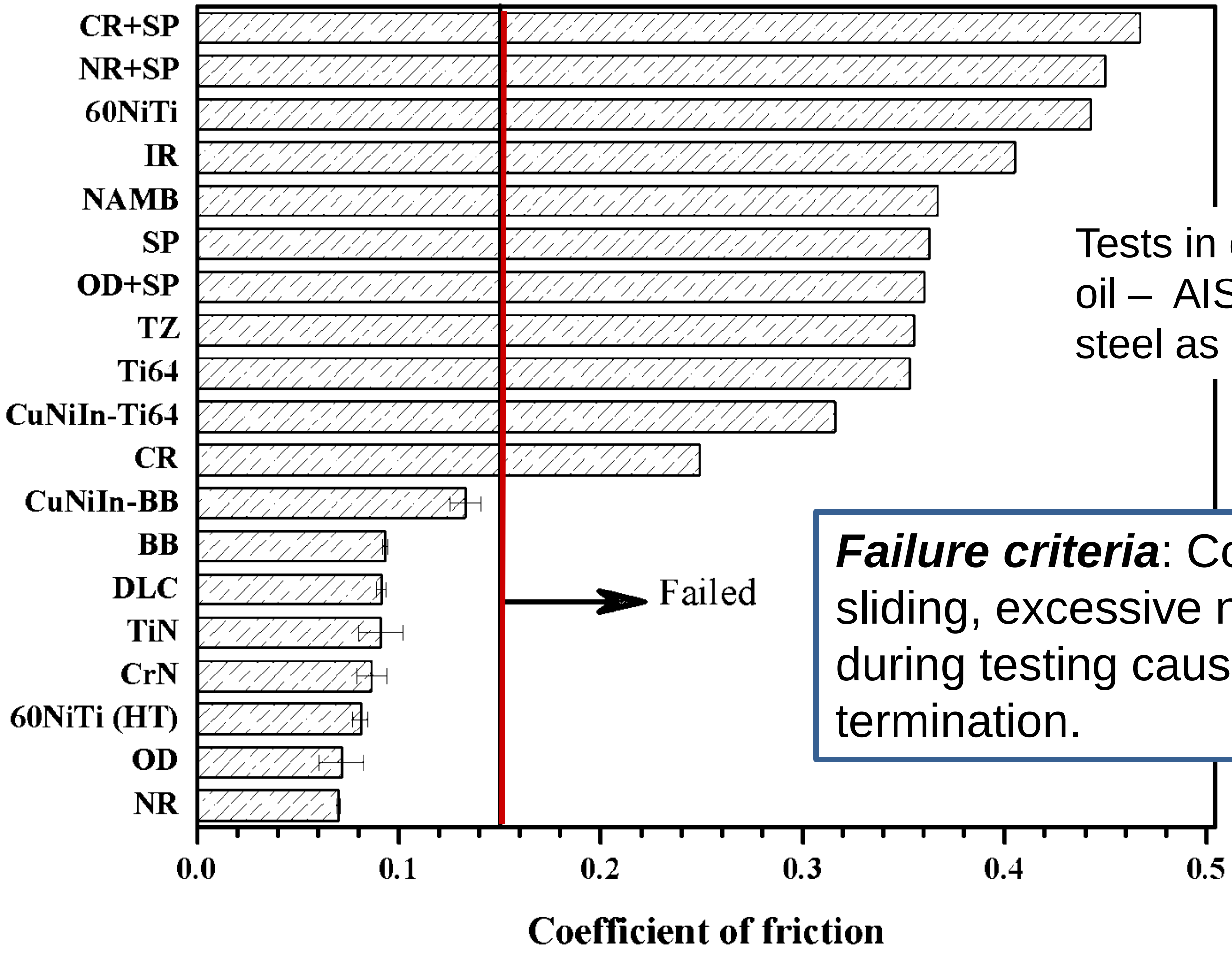
Modified Procedure B: Load = 200 N, 10 mm stroke, 10 cycle/s, 400 m sliding distance, lubricated,* room temperature





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

Technical Progress Phase I: 8 of 19 ‘passed’

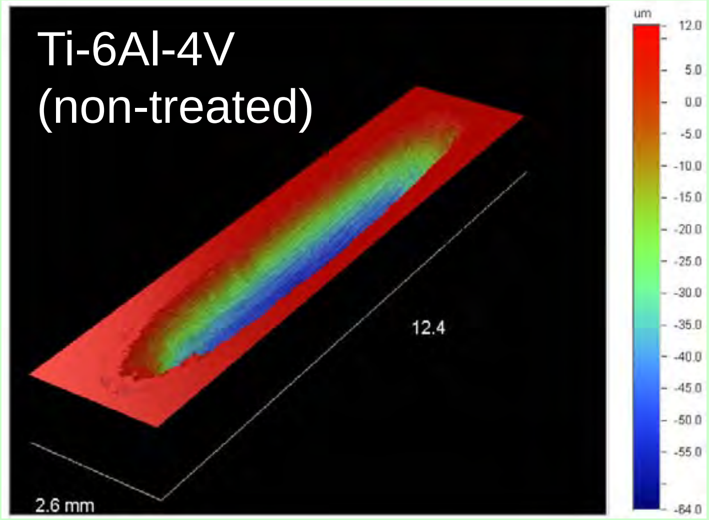


Tests in diesel engine drain oil – AISI 52100 bearing steel as the sliders

Failure criteria: CoF > 0.15, unstable sliding, excessive noise or vibration during testing causing premature test termination.

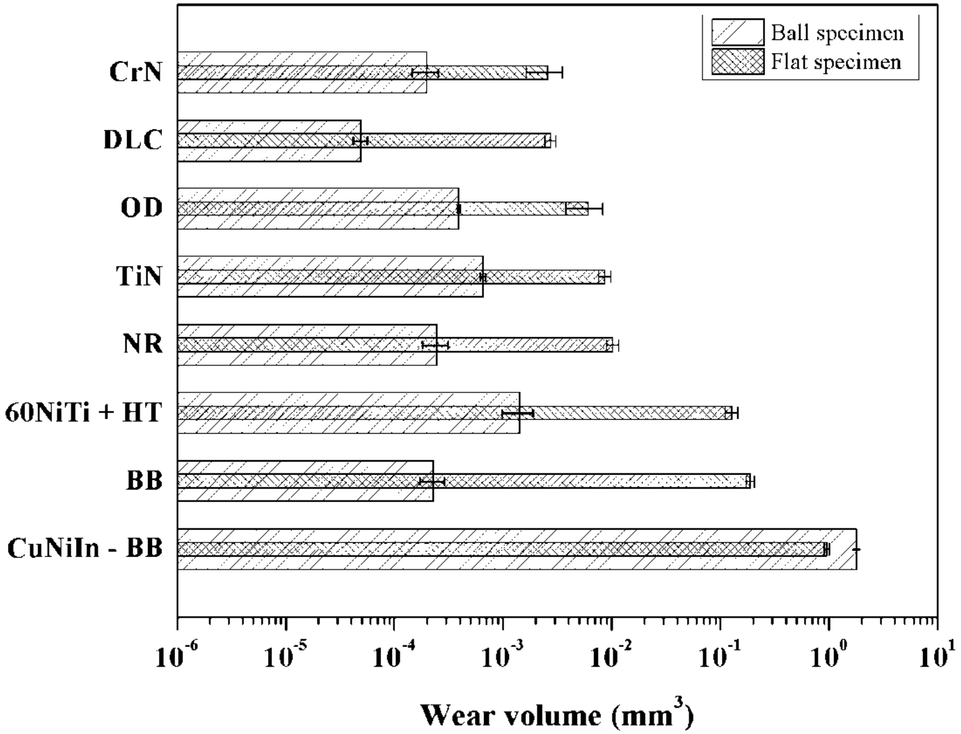
Technical Progress: Wear Test Results*

Wear of both the (Ti) flat specimens and the opposing bearing steel sliders was measured to assess the total tribosystem wear



Wear scar volume was measured by vertical scanning interferometry ***(HTML, Tribology Research User Center)***

The flat specimen usually wore more than the slider, but not always.



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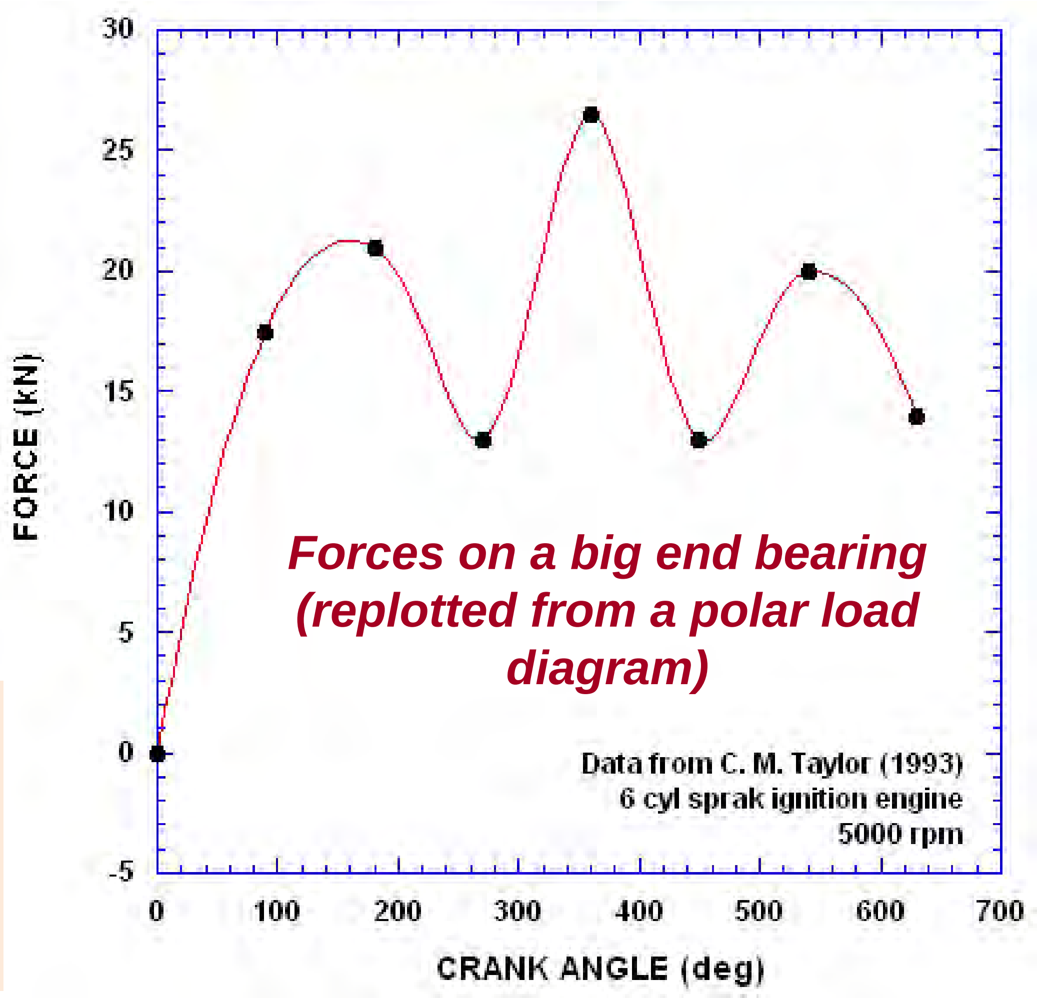
* D. Bansal, O. L. Eryilmaz, and P. J. Blau, pres. at the *International Conference on Wear of Materials* (Philadelphia, April 2011), and published in *Wear* journal (in press, 2011).

Due to engine dynamics, connecting rod bearings operate under varying 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.

A variable-load bearing testing system can provide a more realistic simulation of the stresses on large-end bearings during use.

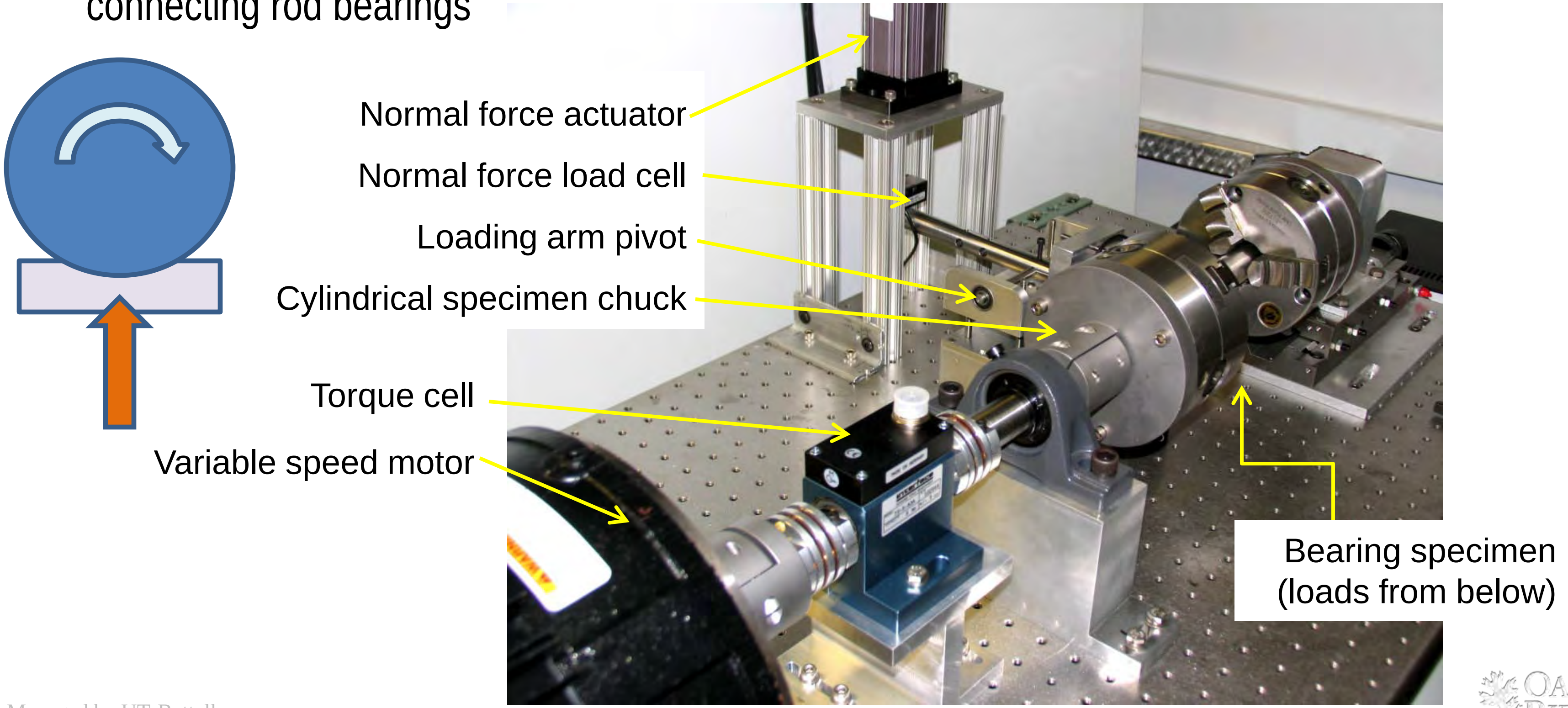


Forces on a big end bearing (replotted from a polar load diagram)

Data from C. M. Taylor (1993)
6 cyl sprak ignition engine
5000 rpm

A Variable Load Bearing Test System (VLBT) was Designed and Built at ORNL

- Torque, speed, normal and tangential (friction) force measurement
- Spectrum loading capabilities to provide for ranges of lubricant behavior (mixed regime, boundary lubrication, dry or starved, etc.)
- Fixtures were designed to accommodate both simple specimens and sections cut from actual connecting rod bearings



Technical Accomplishments and Progress*

- **Conducted baseline friction and wear tests**. Selected test method (ASTM G133 – Procedures A and B), and conducted reciprocating pin-on-flat tests on 21 materials, coatings, and surface treatments to down-select materials for Phase II. Published and presented results.
- **Designed, variable-load bearing test system (VLBT).** Procured commercial parts and computer, machined fixtures, installed sensors and loading system, programmed computer for control and force measurement, conducted calibrations and baseline tests on bronze and non-treated Ti-6Al-4V.
- **Signed NDA with Cummins** to share information on lightweight connecting rod requirements.
- **Conducted additional, studies of the leading surface engineering treatments to evaluate repeatability of performance.** Based on initial results, are re-running some G133 experiments while also preparing optimized specimens for VLBT testing.

Collaboration and Coordination with Other Institutions / DOE Projects

- ☐ **Cummins Engine Company** (Columbus, IN) – discussions and advice on applications for Ti in diesel engine components,
- ☐ **NASA, Glenn Research Center** (Cleveland, OH) – Exploring a novel Ti-based intermetallic alloy for a possible surface alloying approach.
- ☐ **Argonne National Laboratory** (Argonne, IL) – Provided DLC films on Ti and is a co-authoring the Wear of Materials Conference paper (2011)
- ☐ **Eaton Corporation/Ames Lab** (Southfield, MI) DOE/ITP Project on Nanocomposite $AlMgB/TiB_2$ composites.
- ☐ Commercial suppliers**:** **Phygen Coatings** (Minneapolis, MN), **Tiodize** (Huntington Beach, CA), **Solar Atmospheres** (Souderton, PA), and **Metal Improvement Company** (Paramus, NJ)
- ☐ **ORNL** – Two LDRD funded projects on (a) IR-treated Ti to resist galling, and (b) Ti composite armor using P/M processing methods

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 variable loading bearing test system.

FY 2011:

- Variable load testing of the leading candidates coatings and treatments.
- Confirm plans for scale up of the concept validation in year 3, if funding permits.

ACKNOWLEDGEMENTS

Special thanks to D. Bansal and K. Cooley, ORNL, who assisted in tribo-testing, wear measurements, and VLBT apparatus construction.

Wear tests and measurements were made on instruments in the DOE/EERE/OVT High Temperature Materials Laboratory (HTML), Tribology Research User Center.

Summary

- Improvements in surface properties and raw material cost reductions by emerging processes, enable new uses for lightweight Ti alloys in energy-efficient engines.
- Integral big-end bearing surfaces of connecting rods were selected to demonstrate surface engineering approaches and to eliminate lead-bearing bronze inserts from vehicles. Other applications for Ti-based bearing surfaces are possible.
- A literature review, coupled with past OVT-sponsored ORNL tribology work, helped identify and down-select candidate surface treatments and coatings. Tests of 18 candidates in FY 2010 (Phase I) revealed 8 with promising performance for further study in FY 2011 (Phase II).
- Following initial laboratory-scale screening tests of bare, treated, and coated Ti coupons, a variable load test system was designed and built to simulate time-varying lubrication regimes in lubricated bearings.
- Phase III, if funded, will focus on prototype Ti connecting rod development.