Boundary Layer Lubrication

Oyelayo O. Ajayi
Argonne National Laboratory

Sponsored by Lee Slezak
Heavy Vehicle System Optimization

Team members
Cinta Lorenzo-Martin
Robert Erck
George Fenske
Jules Routbort
Ali Erdemir
Osman Eryilmaz

DOE VEHICLE TECHNOLOGIES
PROGRAM ANNUAL MERIT REVIEW
February 25th, 2008

“This presentation does not contain any proprietary or confidential information”
**Impact of Friction Reduction on Vehicle Efficiency**

- Friction reduction by effective lubrication can translate to significant Fuel savings

- Analysis shows possible efficiency gain by friction reduction - > 5%
  - Translates to 1200 M gallon of diesel fuel saving per year (about 240 M gallon saving/% efficiency gain)

- Engine - >4%
  - Axle – 2%
  - Transmission - 3%

Argonne National Laboratory
Higher Power Density and Size Reduction

- Components and system power density increase will lead to significant increase in efficiency
  - Size and weight reduction
  - 5 – 15% fuel savings possible (significant annual fuel savings)

- Power density increase leads to higher contact severity
  - Component may operate mostly under boundary lubrication
  - Exceed material capability – failure
Purpose of Work and Justification for Project

Achieving sustainable friction reduction and scuffing prevention with increasing power density requires better understanding of boundary lubrication.

Boundary lubrication is complex:
- Poor understanding of chemical films and near-surface material behavior

Biggest payoff in terms of friction reduction is in the boundary regime.

Goal: Develop better understanding of boundary lubrication mechanisms and the failures therein using a system engineering approach.
**Benefits**

- Improve efficiency of exiting systems and components
  - Predictable friction reduction

- Facilitate effective new lubricant formulation for friction reduction and non-ferrous surfaces

- Facilitate development of smaller, more efficient high power density systems and components
  - Without sacrificing reliability and durability

- Applicable to ALL heavy vehicles regardless of powersource or fuel.
**Approach: System Engineering**

**Project Plan and Structure**

- **Materials**
  - Near-surface-material dynamic changes: - scuffing
  - Basic mechanism of scuffing failure
    - Prediction and prevention
  - Role of surface modification: - coatings

- **Chemical Films**
  - Boundary film formation and loss rate: - APS, other surface analysis tools
  - Mechanical and friction properties of boundary films measurement
  - Models for film formation, mechanical and frictional behavior

**Integrate both elements with EHD to formulate failure/performance prediction methodology for lubricated components**
Technical Accomplishments to Date

- Extensive characterization of the dynamics of near surface material changes during scuffing process by cross-sectional microscopy

- Developed and validated a scuffing model for metallic materials:
  - Scuffing initiates by adiabatic shear instability – can predict shear strain required for scuffing initiation
    \[ \gamma = \frac{n \rho C_v}{0.9 \frac{\partial \tau}{\partial T}} \]
  - Scuffing propagates by contact interface heat management

\[ V = \frac{d\delta}{dt} = \frac{\beta \tau \dot{\gamma}}{\rho C} - \frac{\lambda}{\rho C} \left( \frac{\partial^2 T}{\partial X^2} \delta - \frac{\partial^2 T}{\partial T} \frac{\partial T}{\partial X} \delta \right) \]

- Both scuffing initiation and propagation can now be quantitatively connected to material properties
**Technical Accomplishments to Date**

- Based on material properties, ceramic/contact pairs showed significant scuff resistance.
  - CSI = $\mu L S$ - measures frictional energy to cause scuffing

- Scuffing in ceramic/metal pairs involves metal transfer to ceramics

- Other energy dissipation mechanisms were observed
  - Phase transformation, cracking
**Technical Accomplishments to Date – Tribo films**

- Demonstrated usefulness of x-ray based surface analytical techniques for boundary layer characterization at APS in Argonne
  - X-ray fluorescence, x-ray diffraction, X-ray reflectivity

- Designed and constructed x-ray accessible tribometer for XRF

- Useful results, but more information needed
  - Plan to redesign rig – suitable for in-situ testing at APS

![Diagram showing load and fricition coefficient graph with Zn/area and Mo/area data points.](image)
Technical Accomplishments to Date - Temperature

- Temperature has significant effect on boundary layer formation – as expected.
- Need to measure the real temperatures at the points of contact where surface reaction occurs.
FY 08 Work Plan and Accomplishments to date

- Microscopy and profilometry of tribo-chemical films
- Continue evaluation of scuffing mechanisms for non-metallic materials
  - Continue refinement of scuffing model
- Initiate the measurement of boundary film mechanical and frictional properties
- Continue the development of real contact temperature measurement in lubricated sliding.

FY08 Accomplishments to date:
- Initiated FIB analysis of low-friction boundary films
- Progress in understanding metal/ceramics contact scuffing mechanism
- Initiated development of a technique to measure real contact temperatures.
FY 08 - accomplishment

- FIB analysis of boundary layer - Learning from nature
FY-08 accomplishment

- Contact temperature measurement – thermoelectric potential approach
- Proof of concept demonstrated.
**Technology Transfer**

- Initiative by industrial collaborator to develop high power density driveline system.

- Initiated collaboration with the two leading lubricant additive manufacturers and a major oil company to apply some of film characterization techniques in their product development.
  - Development of low-friction lubricants
  - Need for lubricant formulation for non-ferrous surfaces
  - Need to reduce, eliminate and/or substitute some additive components
Future Plans

- Continue the study and refinement of scuffing model to include all classes of materials, especially ceramics and thin-film coatings.

- Redesign and refine the x-ray accessible tribometer for in-situ study of film formation at the APS.

- FIB and TEM analysis of low-friction boundary layer films.

- Develop contact temperature measurement technique and apply to lubricated broad spectrum of lubricated contacts.

- Measure and model the frictional properties of boundary layer, and its impact on component performance.

- Integrate models of near-surface material, boundary layer and fluid films to develop a method/model to predict friction and wear between realistic component surfaces in tribological contact.
Summary

- Increase in vehicle systems and components power density facilitated by better understanding and prediction of scuffing will result in significant petroleum displacement
  - Size and weight reduction in many systems
  - Efficient and cost effective product development

- Boundary films can be optimized for low-friction and durable contact interface with adequate information on the formation and loss rates, the structure, mechanical and frictional properties that the current project will provide
  - Effective and efficient lubricant formulation for various materials
  - Prediction of friction for real surfaces and lubricants

- Results of the project have general applicability.

- Potential for 5 -15 % fuel savings increasingly achievable
The end
Additional materials
Publications, Presentations, Patent

- 12 Peer reviewed Journal publications
- 6 Peer reviewed conference proceedings
- 15 Conference presentations
- 6 Reports
- 1 patent application, and 1 invention disclosure
**DOE Technical Barriers addressed by Project**

Vehicle Technologies program mission – Develop more efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum.

- “Develop technologies to reduce the parasitic losses from heavy vehicle systems”

- From 21 CTP technology road map: “Friction, wear, and lubrication limit engine efficiency. Higher in-cylinder temperatures necessary for higher efficiency require significant advances in tribology”

- Stated need: “Develop a better understanding of frictional effects, and develop materials and lubricants with enhanced tribological properties to address the multiple surface interactions that occur in heavy vehicle systems”.
Background - Lubrication Regimes

Three main lubrication regime depending on the ratio of lubricant film thickness to the composite surface roughness – so called $\lambda$ ratio

Lubricant fluid film knowledge relatively matured through elastohydrodynamics (EHD) theory and experiments

Boundary lubrication is complex:
– Poor understanding of chemical films and near-surface material behavior

Biggest payoff in terms of friction reduction is in the boundary regime.
Challenges of Boundary Lubrication

- Boundary lubrication regime involves the three structural elements simultaneously and changes continuously with time.
  - Requires system engineering approach of integration of the behavior of the three elements.
  - Current approach is Edisonian trial and error.

- Unable to characterize formation and properties of boundary films and changes in material surface in real time.
  - Post-test analysis after surface cleaning.
  - Parametric studies for wear and scuffing

Opportunity:
New tools and technology to facilitate in-situ analysis of boundary film formation and properties measurement, as well as dynamic changes in material surface.
- APS at Argonne
- Scanning probe microscopy (AFM, STM ...)
- Nano indentation