Boundary Lubrication Mechanisms – A Systems Approach

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OFCVS Heavy Vehicle Systems
Program Review
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Identified 21st Century Truck Program Technical Need

- 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.
  - An important means to reduce parasitic loss
Tribology dependent systems in Heavy Vehicles

- Friction reduction by effective lubrication of pertinent components can translate to significant improvement in system efficiency.

- Analysis shows possible efficiency gain
  - Engine - > 4%
  - Transmission - 2 – 5%
  - Axle - 2%

Diesel engine
- Ricardo
- Caterpillar

Axles
- Eaton

Transmission
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
Project Goals and Technical Approach

Develop better understanding of boundary lubrication mechanisms and the failures therein using a system engineering approach – Facilitate development of reliable low-friction components and systems.

• Characterize dynamic changes in the near surface material during failure (catastrophic scuffing as a model) – materials development.

• Determine basic mechanism of chemical surface film lubrication (formation and loss rates, failure mechanisms) – lubricant development.

• Establish and validate frictional performance and tribological failure prediction methodology – integrate into analysis tools.

• Integrate surface modification technologies (e.g. coatings) with lubrication technologies for optimal system performance.

• Transfer knowledge gained and technology developed to industry.
Project Plan and Structure

Near-surface-material dynamic changes: - scuffing

Basic mechanism of failure

Role of surface modification: - coatings

Boundary film formation and loss rate: - APS, other tools

Properties of boundary films

Models for film formation and behavior

Integrate both elements with EHD to formulate failure/performance prediction methodology
Summary of Technical Accomplishments

- Developed a model for scuffing failure in steel material – initiation and propagation stages.
  - initiation based on adiabatic shear plastic instability which occurs when rate of thermal softening exceeds rate of work hardening.
  - Scuffing propagation is determined by contact heat management—balancing heat generation and dissipation.

- Characterized tribochemical films formed by several model lubricant additives with a various x-ray analytical techniques at APS.
  - Showed differences between films generated by two different method from the same additive.
  - Designed and constructed x-ray accessible tribo tester
Scuffing Test

Definition: Sudden catastrophic failure of lubricated sliding surfaces, usually accompanied by rapid rise in friction, temperature, and noise/vibration

- Ring-on-block configuration
- Material: Hardened 4340 steel
- Lubricant: Synthetic basestock
- Speed: 1000 rpm
- Protocol: Step load increase

![Graph showing coefficient of friction vs time with stages labeled: 1. Before scuffing, 2. During scuffing, 3. After scuffing.](image)
**Proposed Scuffing Initiation Mechanism**

Based on microstructural changes during scuffing, adiabatic plastic instability mechanism is proposed for initiation of scuffing failure.

-- crossover point between work hardening and thermal softening

Some criteria for shear plastic instability e.g.

Critical shear strain:

\[ \gamma = \frac{n \rho C_v}{0.9 \frac{\partial \tau}{\partial T}} \]

\(\gamma\) = shear strain
\(n\) = work hardening index
\(\rho\) = density
\(C_v\) = specific heat capacity
\(\tau\) = shear strength
\(T\) = temperature
Propagation of Scuffing damage

Sometimes scuffing will initiate without propagating
- Micro-scuffing
- Scuff quenching
Scuffing Propagates – heat generation rate exceeds heat dissipation rate

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

- \( \beta = \) fraction of plastic work converted to heat (0.9)
- \( \tau = \) Shear stress
- \( \lambda = \) Thermal conductivity
- \( \gamma = \) Strain rate

Simplified governing equation for scuffing propagation - 1D
Further Development

- Extension of the scuffing model to other materials
  - Non-ferrous materials: Cu, Al, Ti alloys
  - Ceramic material: single and polycrystalline
  - Thin film coatings

- Incorporate other material behavior into a comprehensive model
  - Fracture
  - Phase transformation
**Technological Implications**

- Pathway to select and/or develop materials for high power density components and systems.
  - Major impact on vehicle efficiency
  - There are other material requirements for high power density

- Predict scuffing resistance based on material properties and behavior.
  - Facilitate efficient design of new systems
  - Effective scuffing prevention strategy
    - *Role of run-in, lubricant formulation, surface modification*

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Shear instability model been used for Caterpillar for scuffing prediction and modeling in component design.
Project Goals and Structure

Near-surface-material dynamic changes: - scuffing

Boundary film formation and loss rate: - APS, other tools

Basic mechanism of failure

Properties of boundary films

Role of surface modification: - coatings

Models for film formation and behavior

Integrate both elements with EHD to formulate failure/performance prediction methodology
X-ray as a surface characterization tool

Various x-ray based, non-vacuum techniques can be used to characterize the surface layer of materials with a boundary films

- Reflectivity (XRR) – Can determine film thickness, roughness and density of surface films
- Diffraction (XRD) – Can determine the structure (xtalline or amorphous), grain size, stress state
  - *Glancing or grazing incident diffraction (GIXD)*
- Fluorescence (XRF) – Can determine chemical composition of films – similar to EDAX in SEM
- Absorption Near Edge Structure (XANES) – Can determine chemical state of elements in the film
- Spectromicroscopy (XSM)
- Others
Our Approach to Tribofilms Chemical Analysis

- Tribofilms form from additives, oil, surface material, and operation environment

- Usual study Approaches:
  - Chemistry and modeling
  - Post-cleaning analysis

- Our approach:
  - In-situ X-rays in and out, nondestructively
  - Post cleaning analysis
Optical Microscopy of Tribo films

- Tribo chemical films are not continuously smooth, but patchy
  - Spatial variability in composition and properties

- X-ray analysis will provide aggregate information
Tribofilms: data and simulation

- Simultaneous high-resolution fluorescence and reflectivity
- High concentration of Zn on the film surface
- Modeled self-consistently
**Tribofilms: Chlorine for Extreme Pressure**

- Model formulated lubricant: chloroform in polyalphaolefin

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**Optical micrograph of surface**

**XRD**

- Shallow penetration
- Deep penetration

Int.

FeCl$_2$
FeCl$_3$
FeCl$_2$

2\(\theta\), degrees, \(\lambda = 1.2362\) nm
In-Situ Analysis

- X-ray Accessible Tribotester construction completed
- Existing tribotester and X-ray detector
- New X-ray source
- Will give quantitative Zn/area during a tribotest
- Formation and loss rates

Schematic top view

Preliminary Test Results

- Test conducted with 52100 steel ball sliding on 1018 steel disc lubricated with POA with ZDDP and MoDTC additives.

- Simultaneous monitoring of the friction behavior and tribo films composition

- Conduct tests with increasing contact severity; different additive composition; …

Optical micrograph of wear track
Summary

- Technical Accomplishments
  - Developed and validated a scuffing model based on material properties
    - *Foundation for development of materials for high power density systems*
    - *Efficient formulation of effective scuffing prevention strategies*
  - Developed X-ray based in-situ characterization technique for boundary at APS
    - *Used x-ray fluorescence, diffraction and reflectivity,*
    - *Designed and constructed an x-ray accessible tribo tester*

- We are on the way to developing durable and reliable low-friction components and systems for heavy vehicles.
  - Potential 5 – 10% overall efficiency improvement.
Future Plans

- **Design and Development of Scuff-Resistant Materials/components**
  - Needed for high power density tribological applications
  - Formulate a comprehensive scuffing model that incorporates observed material behaviors – plasticity, cracking, phase transformation
    - *Other materials – e.g. ceramics*
    - *Work on thin film coatings scuffing*
    - *Other surface modification*
  - Integrate materials, surface modifications (coatings), and lubricant for scuff resistance – system engineering approach
  - Approach: Using the scuffing model design near surface tribological element on base materials that meet other structural requirements – strength, toughness, fatigue strength, ……
    - *High power density systems and subsystems – size and weight reduction*
Future Plans

- **Lubricated Contacts Surface Characterization and Optimization**
  - In-situ tribochemical films structural characterization.
    - Apply several X-ray-based surface analysis techniques available at APS.
    - Model film formation and loss rates.
  - Mechanical properties and failure characterization of tribochemical films
    - Nano indentation and scratching technique
    - Electron microscopy and other imaging techniques.
  - Evaluate the effects of tribochemical films on friction, wear, and scuffing. – implication for lubricant formulation

- Integrate all the structural elements of surface lubrication to minimize friction and wear– materials, surface modification, lubricant basestock and additives.
The End

- Thank You!
Supplemental slides -

- More information – especially on details of test data and results
Progression to Scuffing

Scuffing produced severely deformed surface layer (~20 μm) in fraction of second.
**Phase transformation during scuffing**

With synchrotron radiation at APS, X-ray diffraction analysis shows scuffing causes phase transformation, with formation of austenite.

Data collected beamline 12-BM at APS.
Strain in Scuffed Samples - from peak broadening analysis

Plastic strain buildup in ferrite phase as a function of stage of scuffing and X-ray penetration depth

![Graph showing RMS (non-elastic) strain](image)

Sample and penetration depth, \( \mu m \)

- Unworn, 0.1
- Unworn, 0.4
- Unworn, 1.2
- Before, 0.1
- Before, 0.4
- Before, 1.2
- During, 0.1
- During, 0.4
- During, 1.2
- After, 0.1
- After, 0.4
- After, 1.2

*small grain size

Plastic strain buildup in ferrite phase as a function of stage of scuffing and X-ray penetration depth

Experiment: Jeff Hershberger, ANL
Performed on beamline 12-BM at APS
**Physics-based Approach (SDAT)**

**Surface Distress Analytical Toolkit**

- **Performance Analysis**
- **Failure Prediction**

**Micro Contact Module**
- Mixed Lubrication Module
- Contact Temperature Module

**Material Failure Criteria**
- Surface Texture
- Residual Stresses
- Thin Film Coatings
- Physics-based Failure Criteria

- Film Thickness
- Pressure
- Friction
- Temperature
- Subsurface Stress
- Contact Fatigue
- Scuffing
- Micropitting
- ......
Boundary Films Characterization

Using the APS to analyze boundary lubrication

- Squeeze films in oil: Analyze with XRD
- Surface tribofilms: Analyze with XRF, XRR, XRD
- Near-surface deformation: Analyze with XRD

Diagram showing the contact between a ball and a flat, with layers labeled as follows:
- EHD/Micro-EHD Films (<1 μm)
- Surface Films (<1 μm)
- Near-Surface (50 μm)
- Subsurface (50-1000 μm)
- Core

Labels for regions:
- Oil
- Pressure
- Residual Stress (Bulk)
- Hardness (Case)
- Principal Shearing Stress (r)
- Core

Legend colors for layers:
- Yellow
- Orange
- Blue
- Green
- Purple
- Black
**Tribofilms: Thermal and mechanical ZDDP**

- Quantitative Zn areal density on surface
- Showed differences between films made thermally and mechanically
AFM of Tribofilm

Polished steel sample worn in commercial oil and solvent-rinsed.

Raised areas of tribofilm deposit

Underlying steel polish

Sample and data: J. Hershberger
Tribofilms: XANES results

- Cylinder liners
- Two penetration depths
- Bonding state of atom
- Well-established technique, now done without rinsing

**Zinc**
- Bonded to oxygen and sulfur (not phosphorus)

**Iron**
- Best described as FeO.
  Differences with depth.