Boundary Lubrication Layer Mechanisms

O. O. Ajayi, C. Lorenzo-Martin, R. A. Erck, G. R. Fenske
Argonne National Laboratory

June 10, 2010

Project ID # VSS003

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Overview

Timeline

- Start date - 2004
- End date - 2012
- Percent complete – 85%

Budget

- Total project funding
  - DOE share – 2,500K
  - Contractor share
- Funding
- FY09 – 400K
- FY10 - 225K

Barriers

- **Barriers addressed**
  - Safety, durability, and reliability
  - Computational models, design and simulation methodologies
  - Higher vehicular operational demands

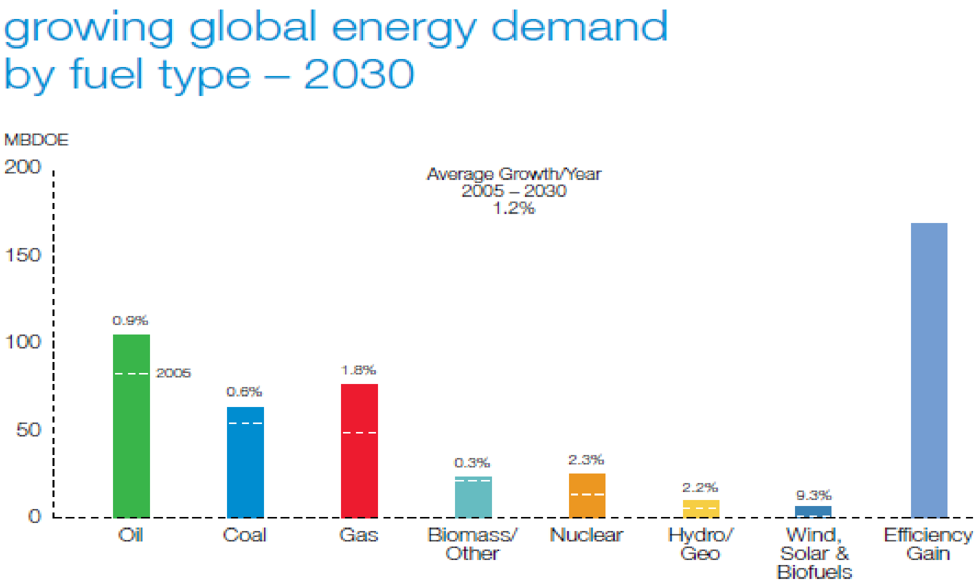
Partners

- Interactions/ collaborations
  - Caterpillar Inc.
  - Eaton Corporation
  - Castrol-BP
  - Oakland University

Largest source Untapped Energy is Efficiency gain

- Efficiency gain is largest source of energy

- In Vehicles, significant fuel savings and consequently imported petroleum oil can be achieved through efficiency gain

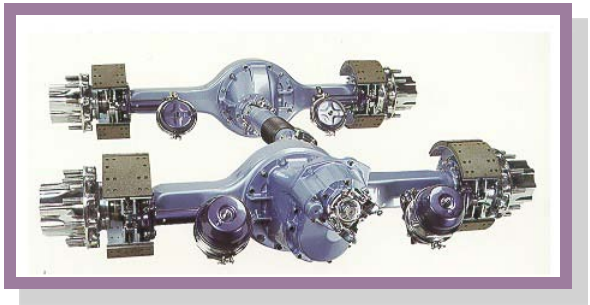


Exxon Mobil-News_pub_2008_energyoutlook

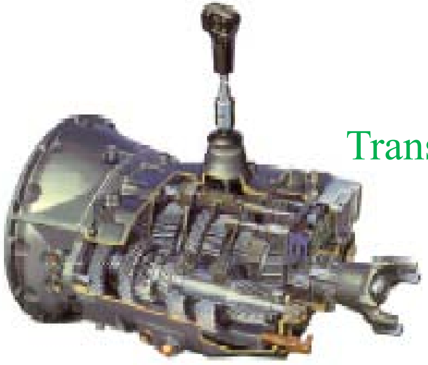
Project Description

Project Conception:

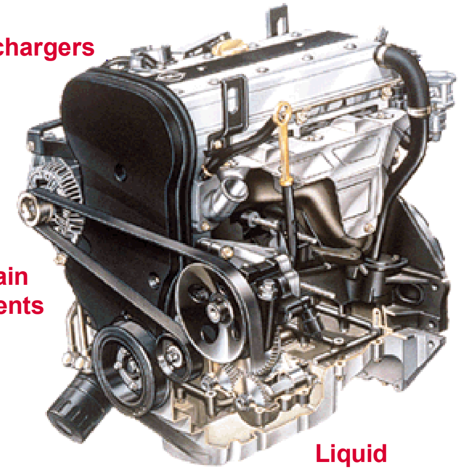
- Friction reduction in vehicle lubricated components and systems translates to improved efficiency.
- Increased power density results in size reduction and fuel saving.
- High friction and high power density failures occur in poorly understood boundary lubrication regime.



Axle -2%



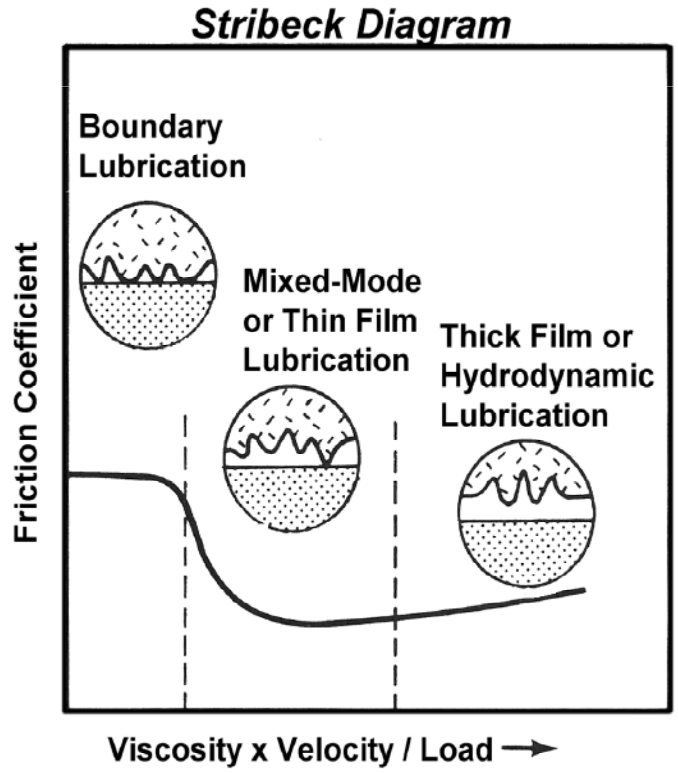
Transmission – 3%



Engine – 4-5%

Overall Project Objectives

- Achieve sustainable friction reduction and increase power density in lubricated components and vehicle systems by developing a better understanding of boundary lubrication mechanisms
  - *Determine the mechanisms of boundary layer formation and loss rates as well as the film properties*
  - *Determine the mechanisms of catastrophic failure by scuffing*
  - *Develop integrated low-friction high power density interface*



Technical Approach

Project Plan and Structure

Materials

Chemical Films

Near-surface-material dynamic changes: - scuffing

Basic mechanism of scuffing failure
Prediction and prevention

Role of surface modification:
- coatings

Determine basic mechanisms of poorly understood near surface material and surface chemical boundary films. Integrate three structural components of lubrication

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 and HD lubrication to formulate failure/performance prediction methodology for lubricated components

Significant Previous Technical Accomplishments

- Developed and validated a scuffing model for metallic materials following extensive microstructural characterization :
  - Scuffing initiates by adiabatic shear instability – can predict shear strain required
  - Scuffing propagates by contact interface heat management
  - Prediction of scuffing from material properties - currently being used as a design guide by one of the industrial partners

- Based on the model, evaluated scuffing resistance of several materials pairs with high scuffing resistance

- Demonstrated the use of multiple x-ray based surface analytical techniques for in-situ characterization of tribochemical boundary films

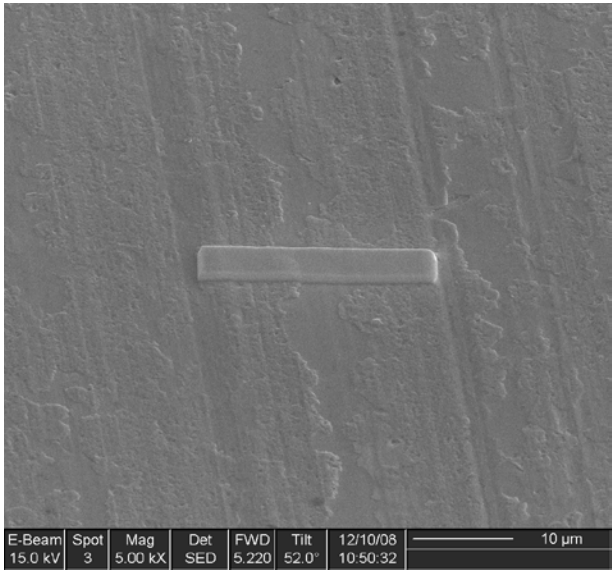
- Initiated development of tribochemical boundary films structural characterization

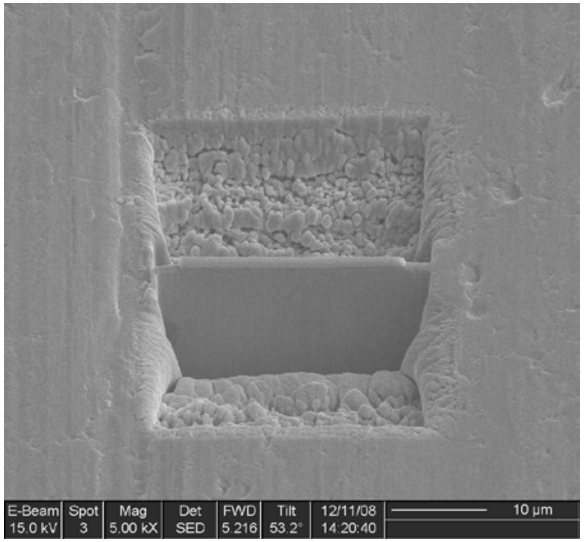
"Take-home" message: - Pathway for high power density material; - pathway to better understanding of tribochemical film structure, properties and performance

FY10 Technical Accomplishments:

- **Developed and demonstrated a unique technique for boundary film structural characterization by combining ion beam milling (FIB) and transmission electron microscopy (TEM)**

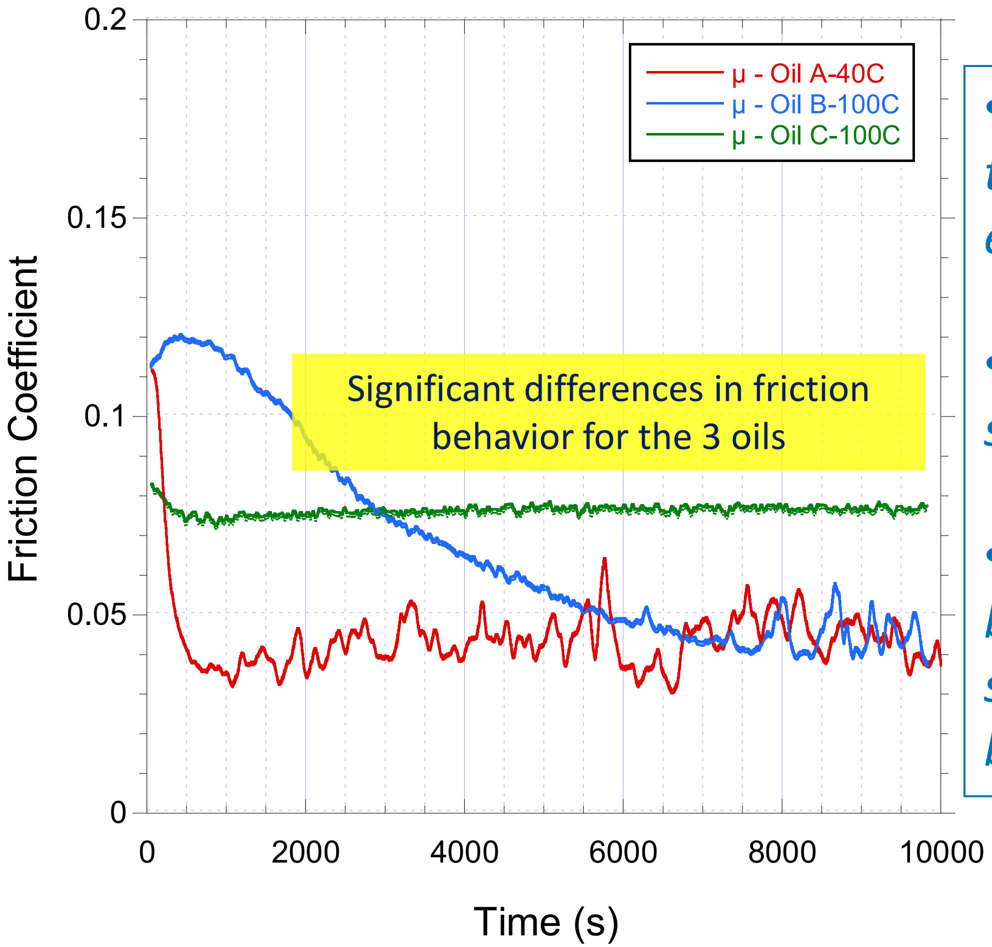
Pt deposited to protect the boundary film during ion beam milling





Cross-section TEM sample prepared by FIB

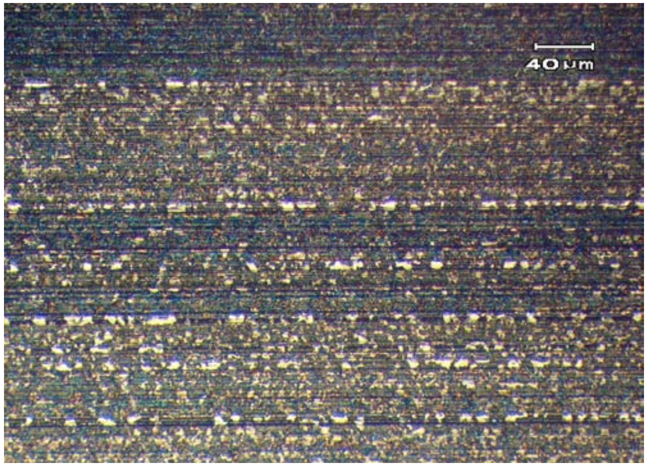
FY10 Technical Accomplishment



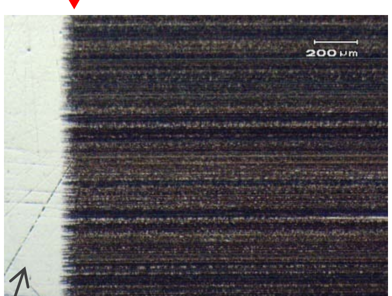
- *The viscosity, and hence fluid film thickness in the three lubricants are equivalent.*
- *Materials for the test are all the same*
- *Differences in friction behavior can be attributed to differences in the structure and properties of the boundary films*

'Take-home' message: Friction behavior of different lubricants reflects differences in the structure of their tribochemical films –pathway to durable low-friction boundary films

Optical Microscopy and profilometry of tribochemical film

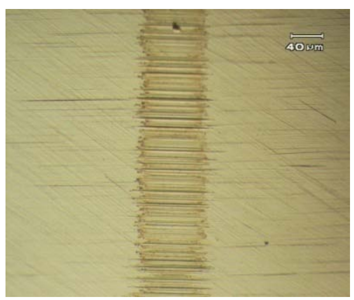


Sliding direction



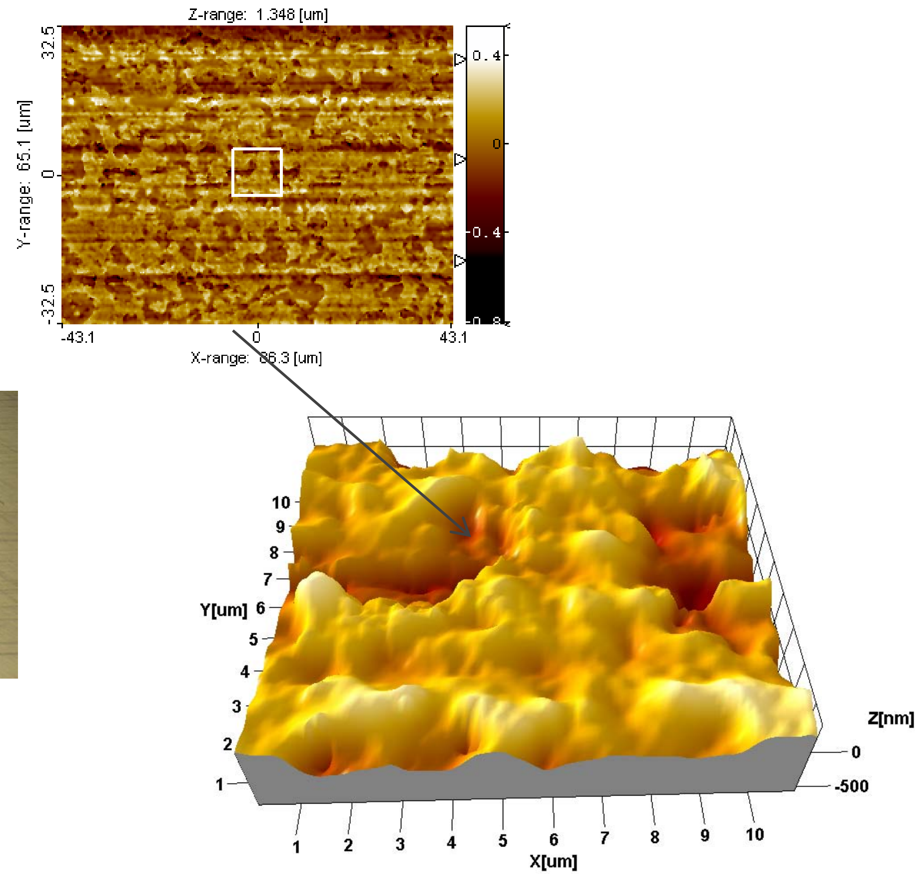
Non-contact area

BLOCK- 1018



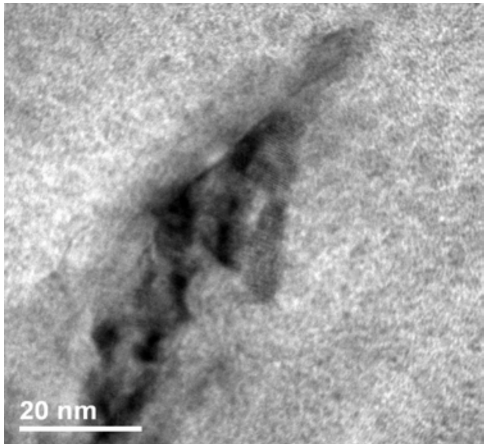
ROLLER-52100

Uniformity in direction of sliding

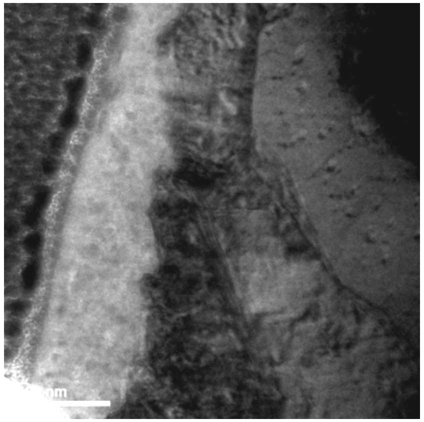


FY10 Technical Accomplishments:

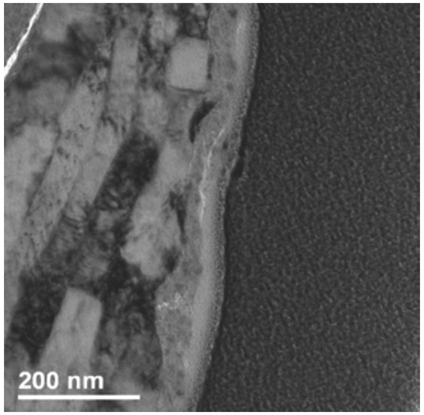
- **TEM analysis showed different features of boundary films produced from different lubricants**
  - **Film thickness 80 – 120 nm range**
  - **Some regions are nano crystalline**
  - **Other regions are amorphous**



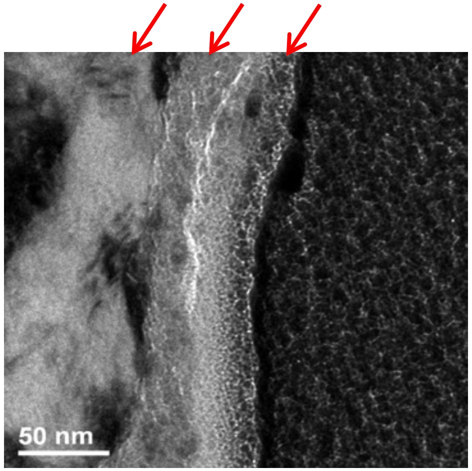
Amorphous region



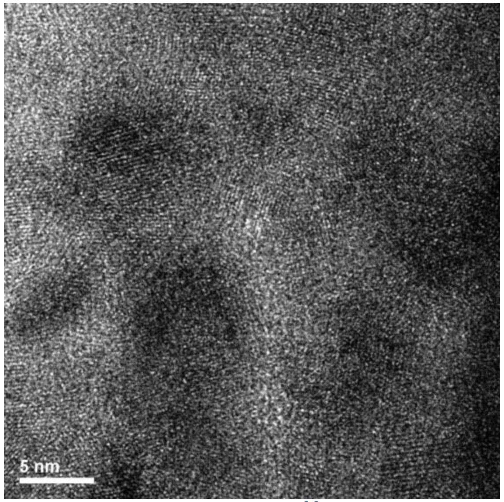
Monolayer film



Bi-layer film

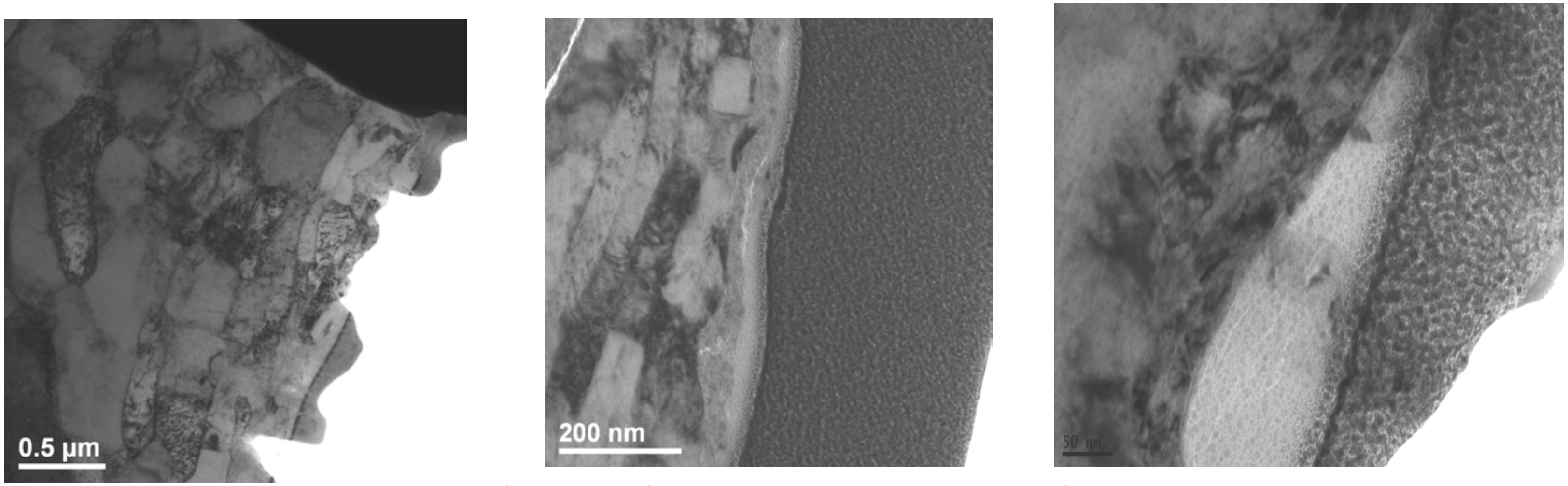


Tri-layer film

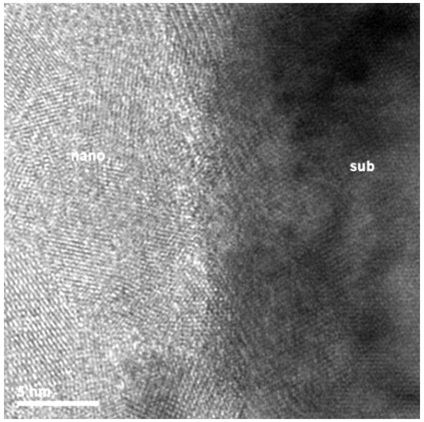


Nano crystalline region
(5-10 nm crystal size)

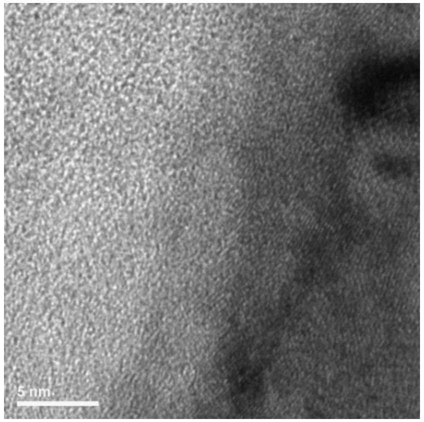
TEM of subsurface and tribochemical (BF) films



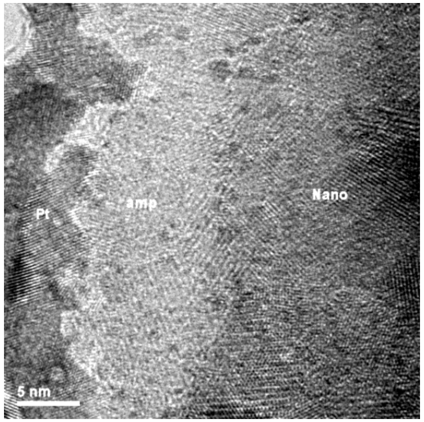
TEM macro image of near-surface material, tribochemical film and Pt layer



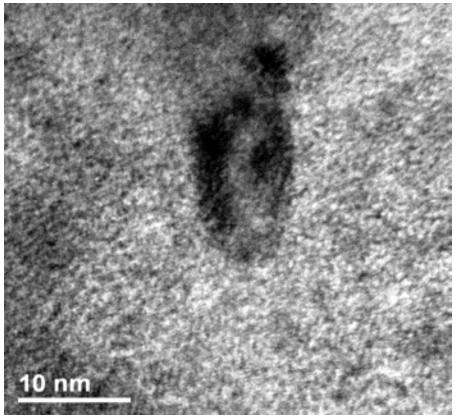
Steel-crystalline BF interface



Steel-amorphous BF interface



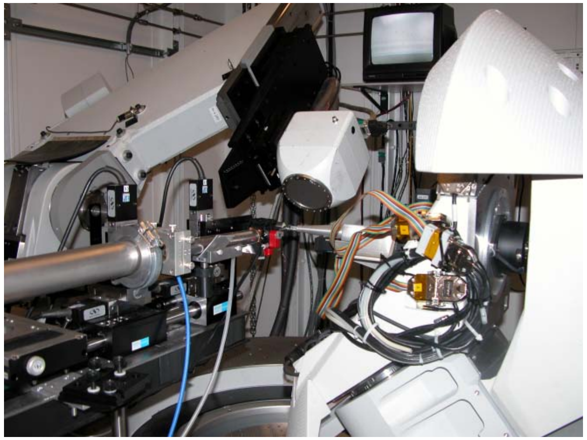
Amorphous-crystalline BF

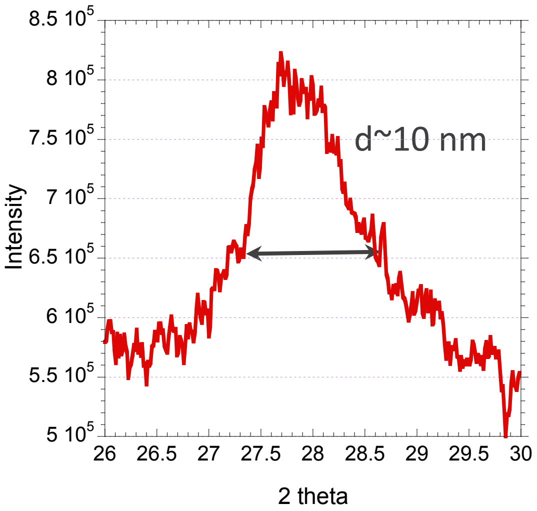


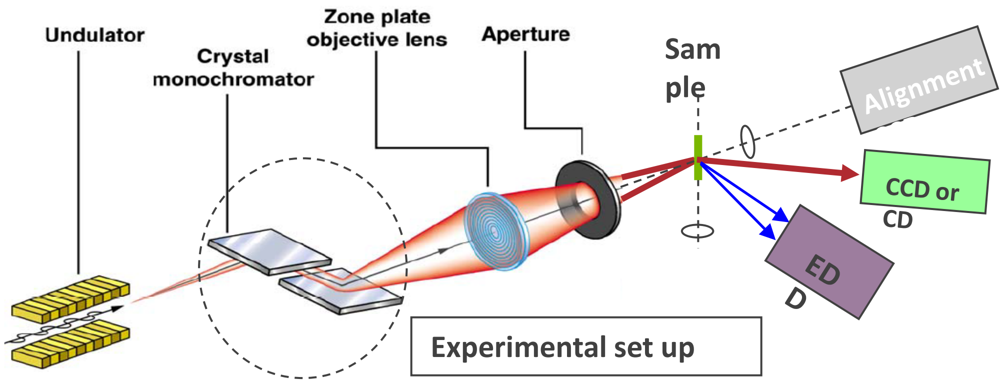
Amorphous BF

Glazing Incidence X ray Diffraction (GIXRD)

- Conducted at Advance Photon Source (APS)
- Beam 2ID-D
- Operating Conditions: E=10.1 Kev., λ= 1.23 Å







PRELIMINARY HIGHLIGHTS

- Broad peaks of tribo-film. Broadness indicative of nano-size of grains
- Indication of some amorphous layer by the reduction of intensity in some films
- So far, results from X-ray analysis are consistent with TEM observations.

FY10 Technical Accomplishment - Boundary film structure and friction behavior connection

- ***Differences in friction behavior can be attributed to differences in the structure and properties of the boundary films***
  - ***Lower friction lubricants (A and B) contain more armphous structure***
  - ***Higher friction lubricant with steady behavior contains mostly nano-crystalline film as determined by X-ray and TEM***

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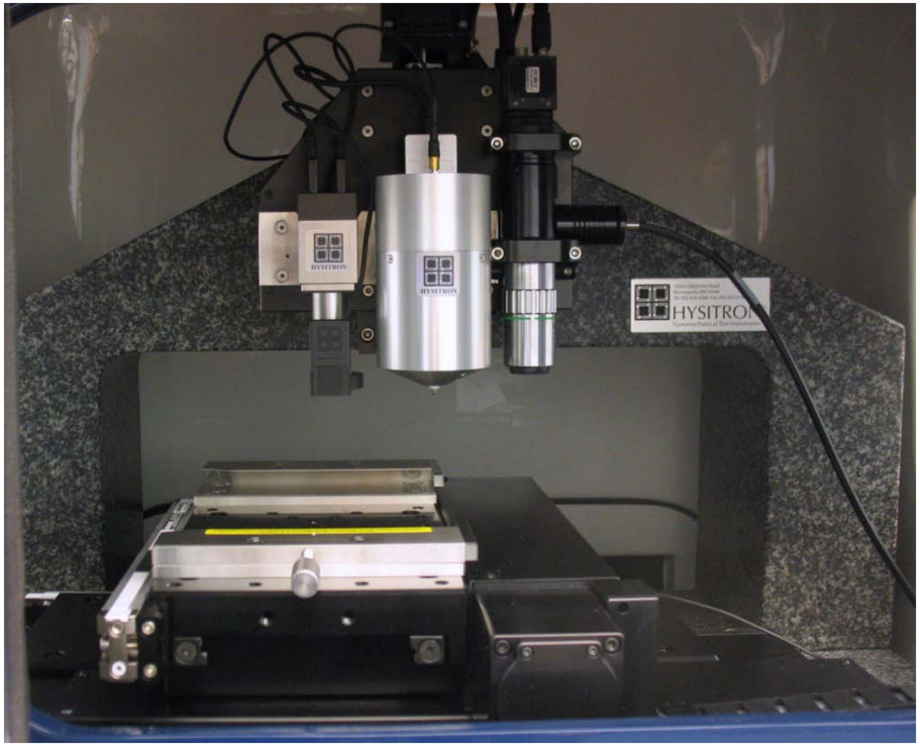
FY10 Technical Accomplishment: Nano Mechanical properties of tribochemical films

- Nano mechanical properties of the tribo chemical films determined by instrumented nano-indenter system

- Tribo film surfaces were first imaged by scanning (AFM) prior to indentation.

- Hardness and elastic modulus of the films are determined.

- Mechanical behavior of the film can also be inferred from the load-displacement curve during loading and unloading.

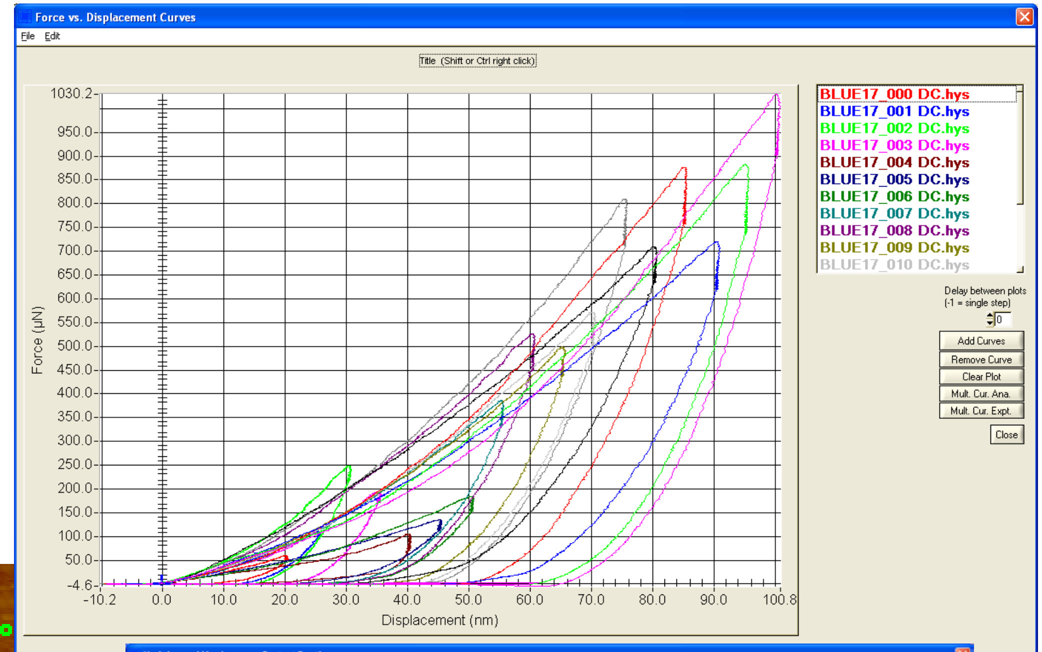


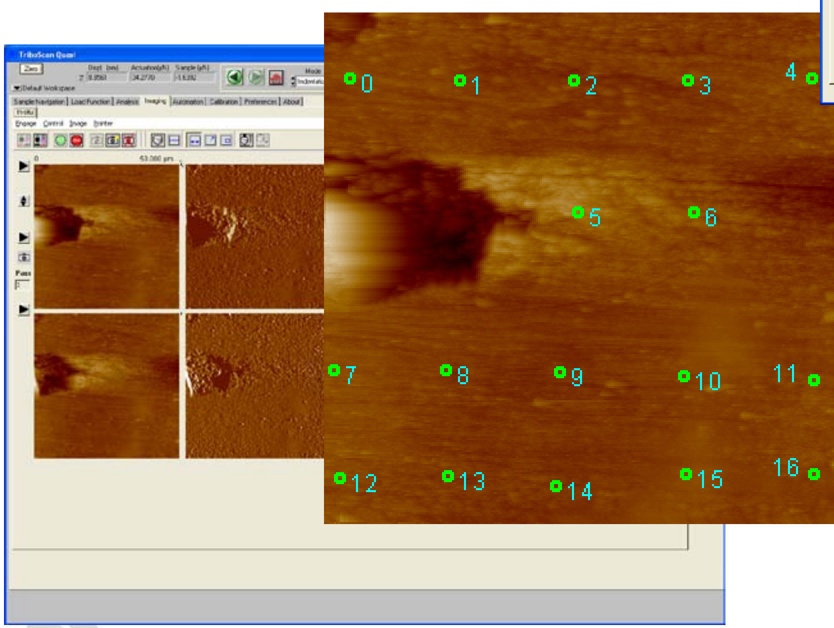
'Take-home' message: Mechanical properties and behavior of tribo-chemical films are dependent on the structure of the films.

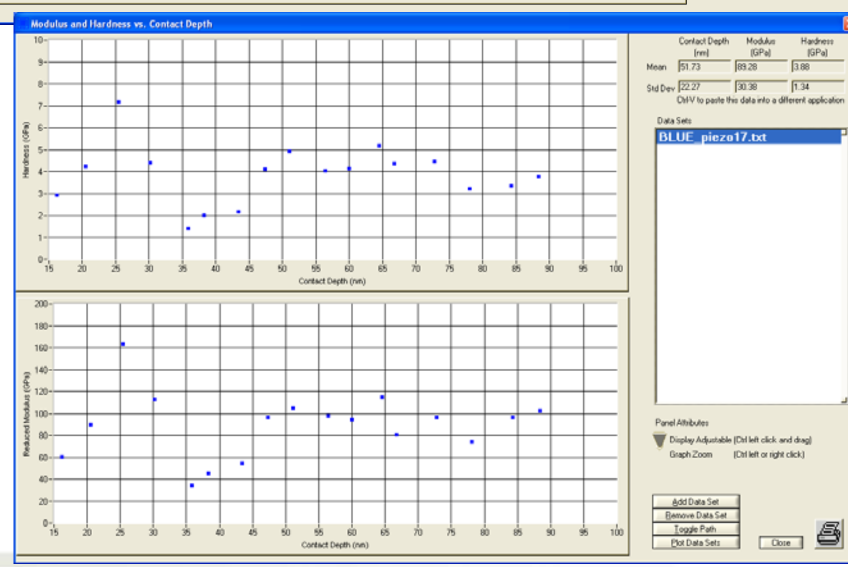
Nano-mechanical properties of Low-friction films

- Hardness - 3.8 GPa
- Elastic modulus – 90 GPa
- Complex mechanical behavior

- Steel substrate – 7.8 GPa and modulus – 200 GPa



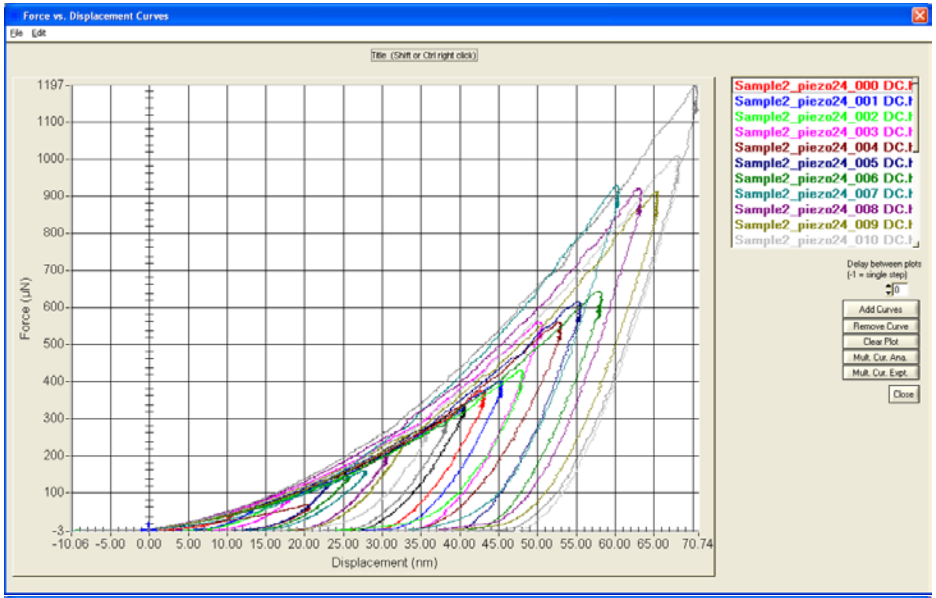


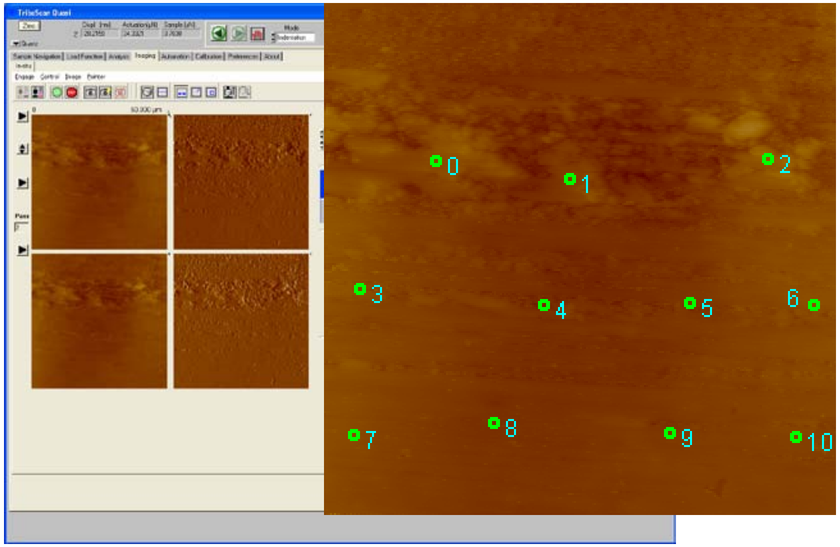


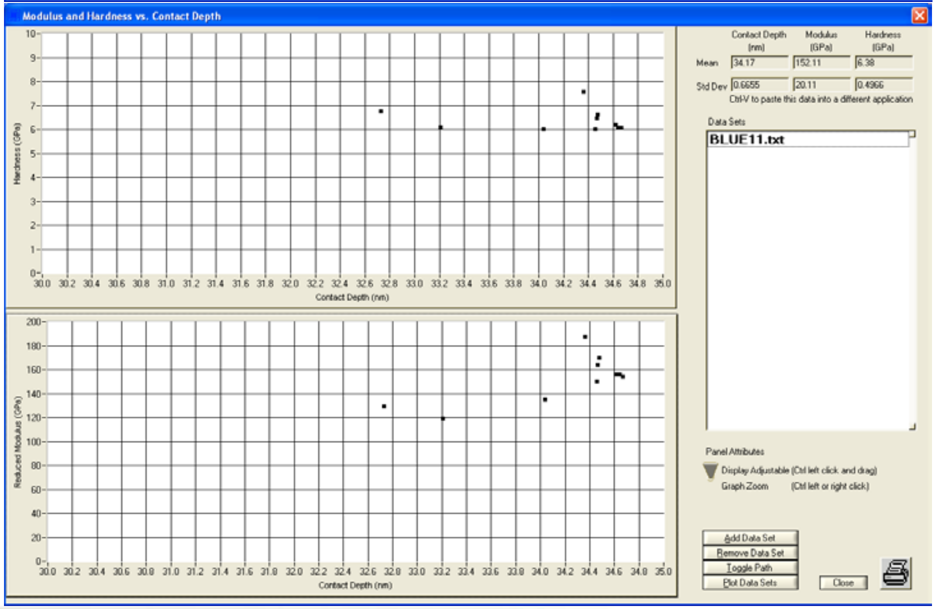
Nano-mechanical properties of higher-friction films

- Hardness - 6.4 GPa
- Elastic modulus – 152 GPa
- Elasto-plastic mechanical behavior

- Steel substrate – 7.8 GPa and modulus – 200 GPa







Collaborations

- **Caterpillar Inc.** (Industry): Collaboration on the validation study of scuffing model.
- **Castrol-BP Inc.** (Industry): Collaboration of the formulation of lubricants to form a variety of different tribo-chemical boundary films.
- **Eaton Corp.** (Industry): Collaboration on the measurement of boundary film structure and boundary lubrication friction for transmission gear oil and materials.
- **Oakland University** (Academic): Collaboration to model contact temperatures and stresses during boundary lubrication sliding contacts.

Proposed Future Work.

- Continue structural characterization of boundary films with differing tribological properties
  - FIB and TEM
  - Glancing incidence X-ray techniques at APS
  - Surface profilometry and AFM

- Continue measurement of nano mechanical and frictional properties of structurally different boundary films using a nano mechanical probe system
  - Provide pathway for structure-properties relationship formulation for boundary layer films
  - Indication of mechanical failure mechanisms of boundary films

- In view of the impact of contact temperature on boundary film formation and frictional behavior, we plan to develop and refine the technique for the measurement of lubricated contact real temperature using the thermoelectric principle. Measurements will be conducted under various contact conditions.
  - Measurement essential to modeling boundary film formation kinetics
  - Input for boundary lubrication friction prediction
  - Assess the correlation of measured and calculated contact temperatures

Summary

- Increase in vehicle systems power density facilitated by this project through 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

- Results of the structure-properties-frictional performance connection for tribochemical boundary films being developed in this project will facilitate achievement of reliable and sustainable friction reduction in numerous pertinent vehicle components and systems
  - Effective and efficient lubricant formulation for various materials.
  - Prediction of friction for real surfaces and lubricants.

- Results of the project have general applicability for all vehicle systems.

- Potential for 5 -15 % fuel savings via efficiency gain is increasingly achievable