Boundary Layer Lubrication Mechanisms

O. O. Ajayi, C. Lorenzo-Martin, N. Demas, R. A. Erck, and G. R. Fenske

Argonne National Laboratory

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Project ID # VSS003

Overview

Timeline

- Start date - 2004
- End date - 2012
- Percent complete – 90%

Budget

- Total project funding
  - DOE share – 2500K
  - Contractor share
- Funding
- FY10– 225K
- FY11 - 300K ?

Barriers

- **Barriers addressed**
  - Constant advances in technology
  - Computational models, design and simulation methodologies
  - Risk Aversion
  - Lack of standardized test protocols

Partners

- Interactions/ collaborations
  - Eaton Corporation
  - Castrol-BP
  - Oakland University

Relevance - Efficiency gain as energy Source

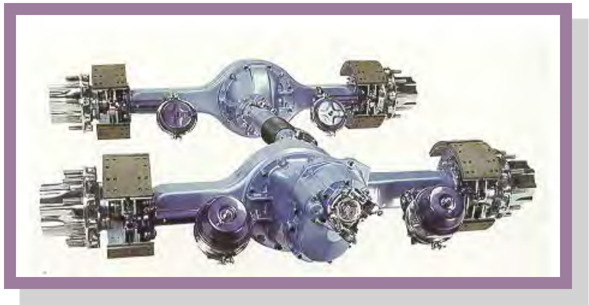
- Efficiency gain is largest source of energy

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

Relevance - Project Description

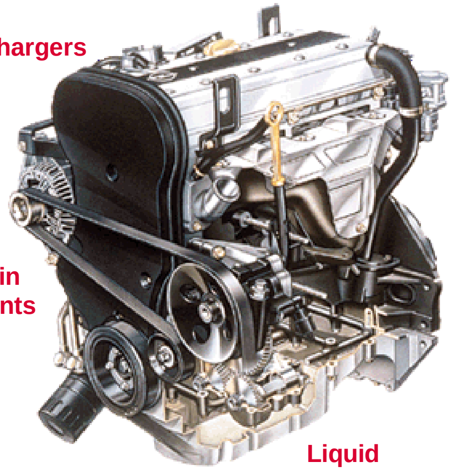
Project Conception:

- 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%

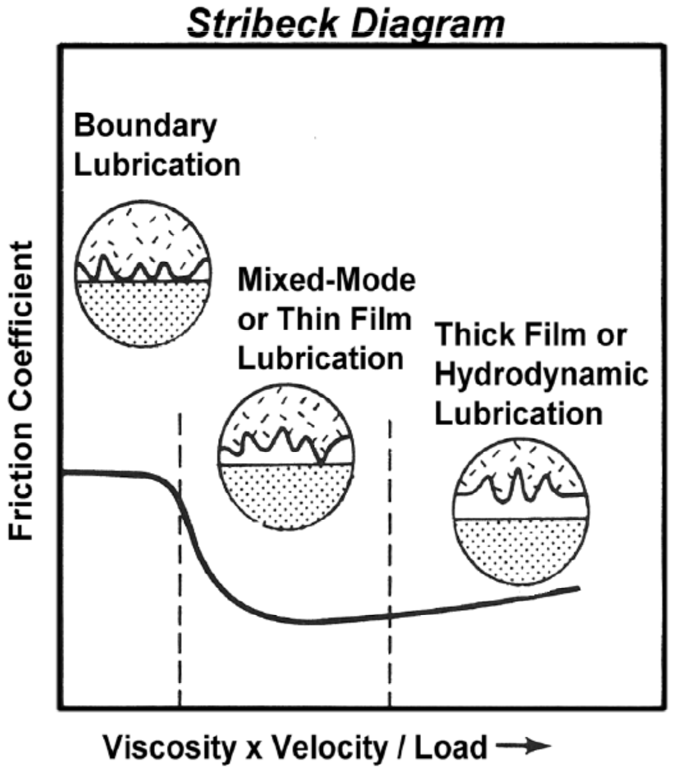
Transmission – 3%



Engine – 4-5%

Relevance - Overall Project Objectives

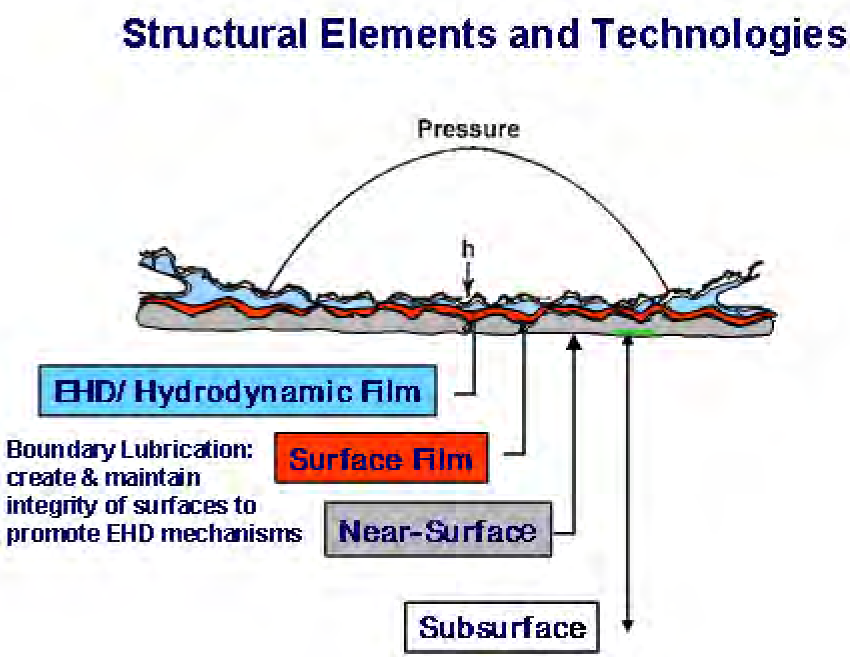
- Achieve sustainable friction reduction and increase power density in lubricated components and vehicle systems by developing a better understanding of boundary lubrication mechanisms
  - *Determine the mechanisms of boundary layer formation and loss rates as well as the film properties*
  - *Determine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



Approach - Lubricated Contacts Sources of Friction

Three structural elements:

- Lubricant fluid films (Hydrodynamic and EHD)
- Tribochemical surface reaction films (boundary films)
- Near-surface materials



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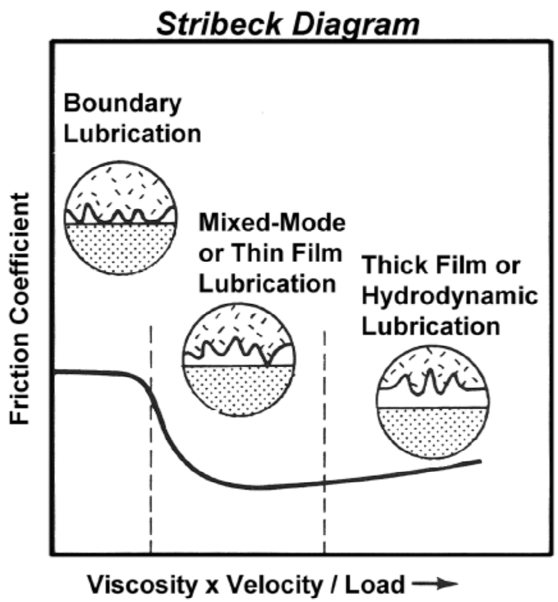


- Highest friction and failure susceptibility occurs in boundary lubrication regime.

- Surface films and near-surface material structural elements dominate friction and wear behavior – these two elements are not included in existing friction models.

Technical Approach

Project Plan and Structure

Materials

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

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 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

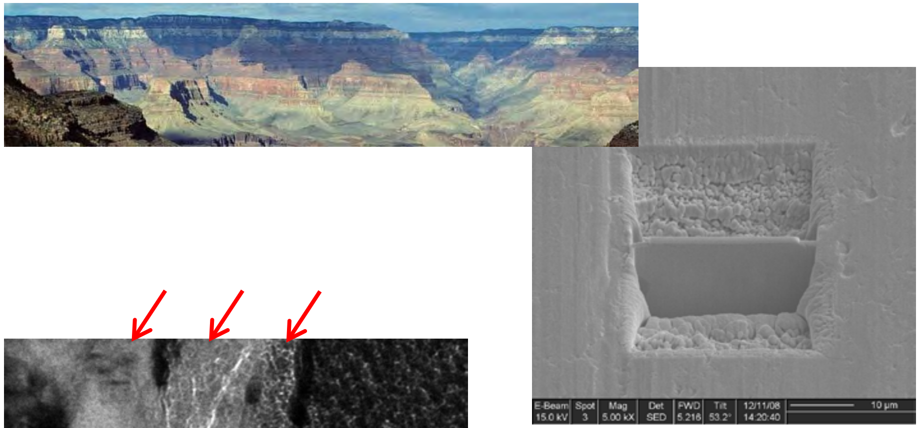
- Demonstrated the use of multiple x-ray based surface analytical techniques for in-situ characterization of tribochemical boundary films

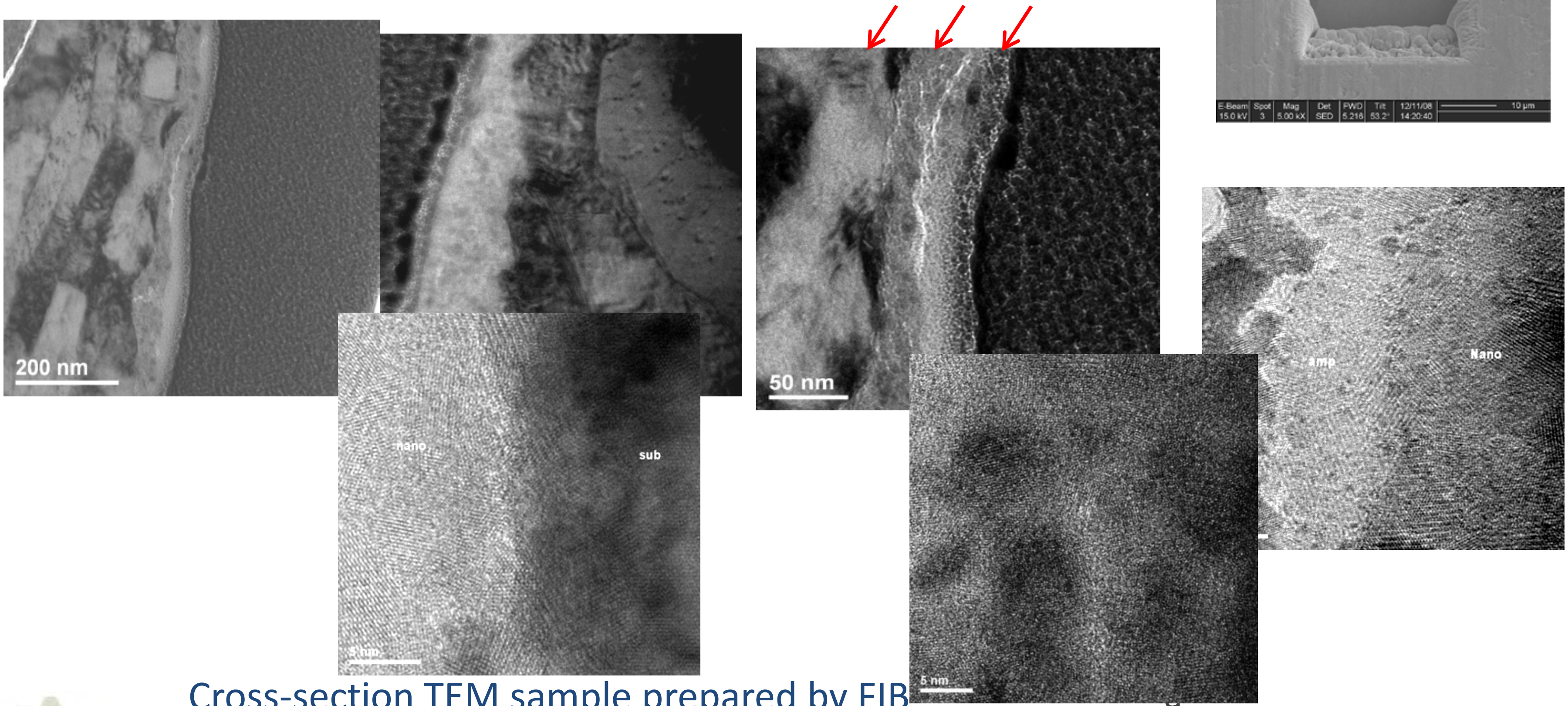
- Initiated development of tribochemical boundary films structural characterization

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

FY11 Tech Accomplishments: Tribo film analysis

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

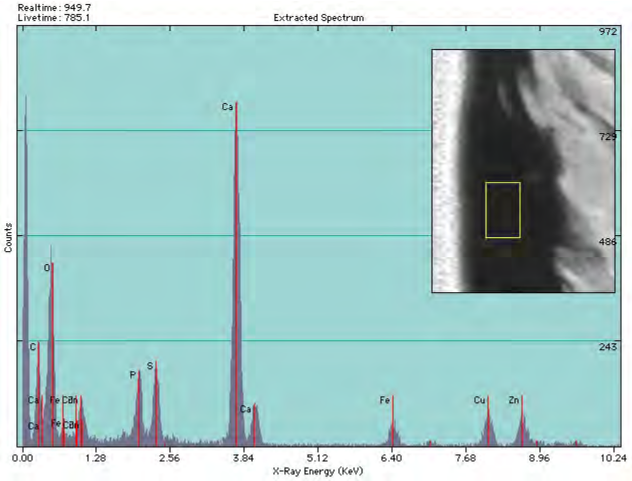


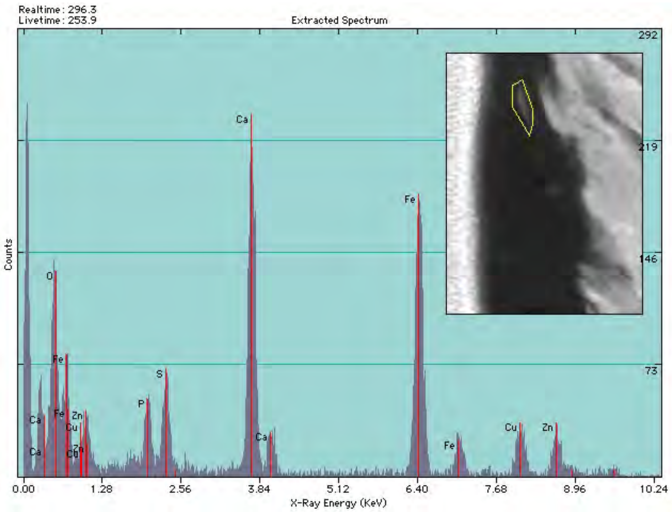


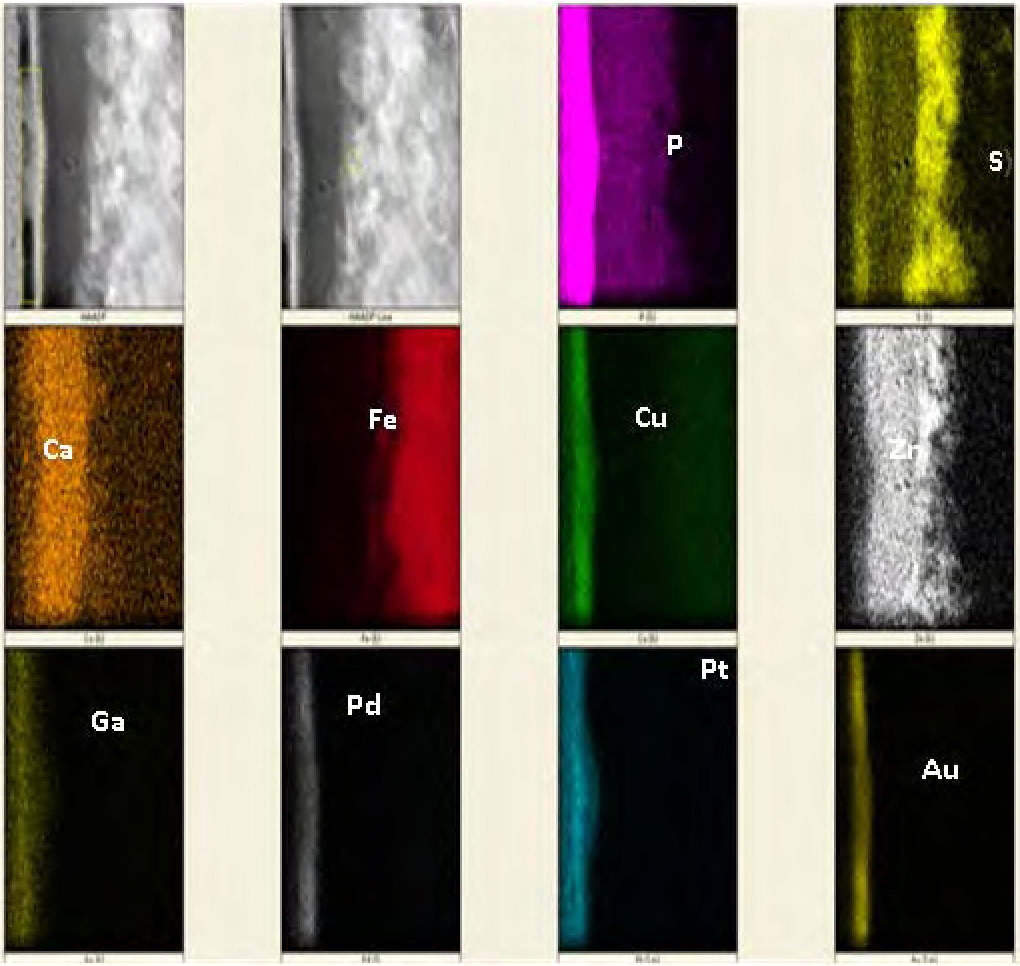
Cross-section TEM sample prepared by FIB

FY11 Tech Accomplishments: Tribo film analysis

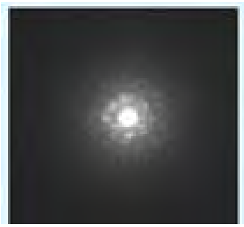
Chemical analysis of tribo film by EDAX of TEM sample shows complex composition

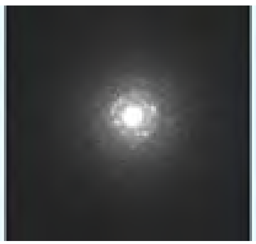


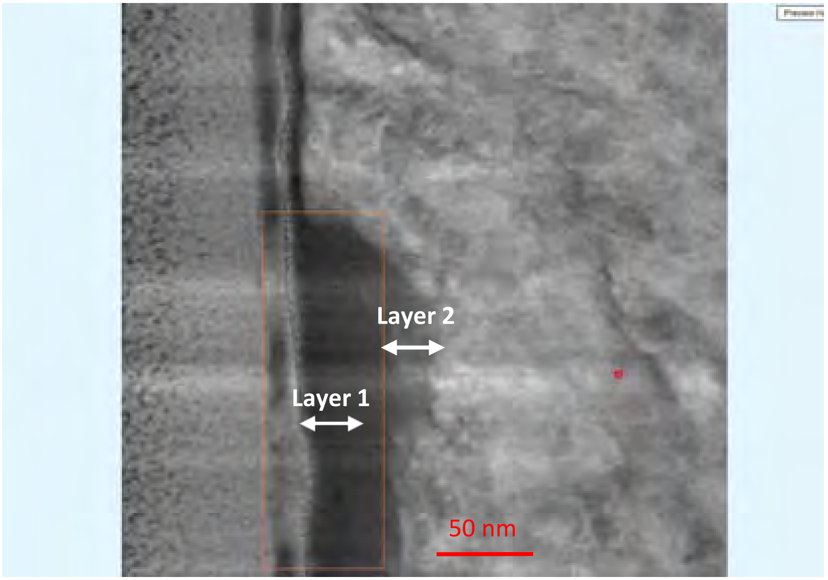


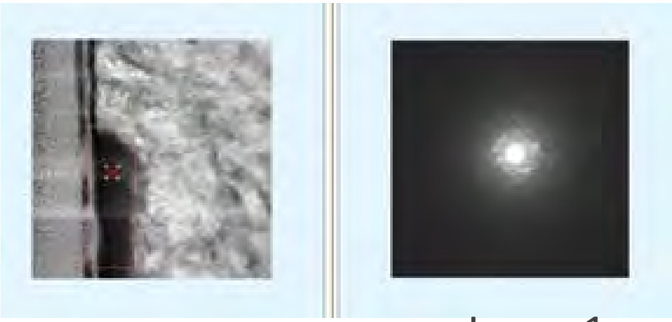


FY11 Tech Accomplishments: Tribo film analysis

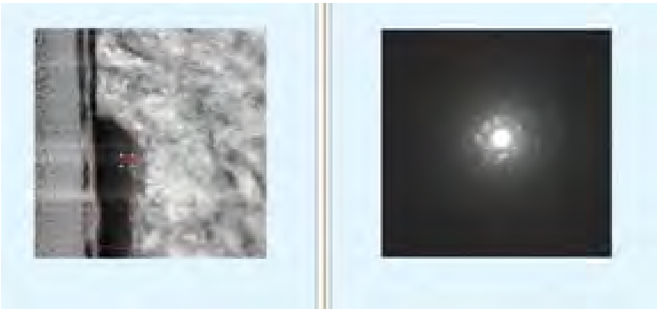




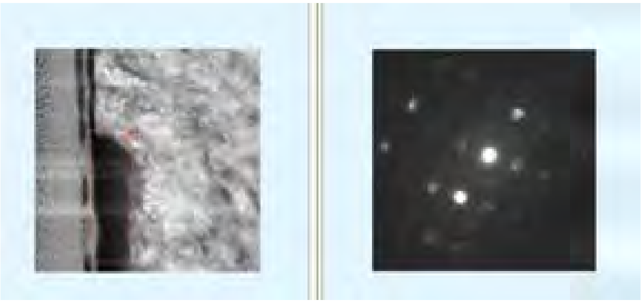




Layer 1



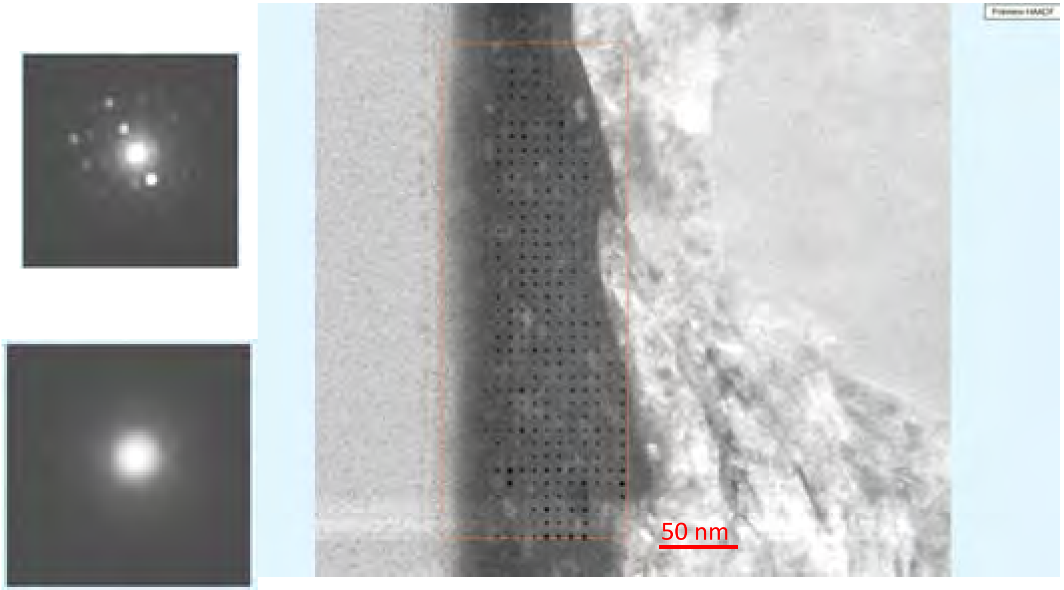
Layer 2

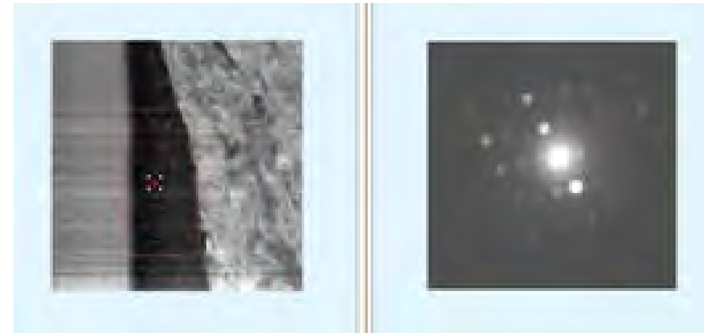


Substrate

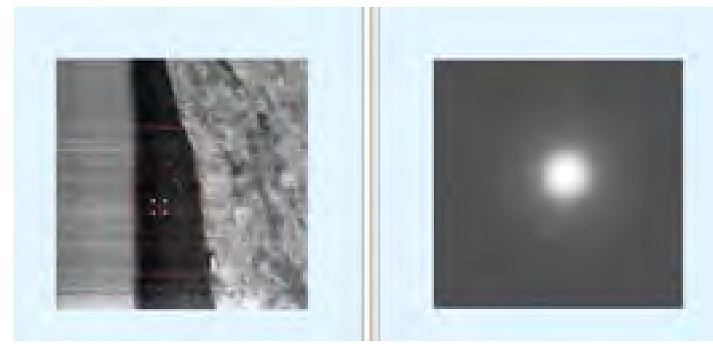
- HIGH FRICTION FILM
- Tribofilm mostly crystalline with an small fraction of amorphous phase in the grain boundaries.
- Total film thickness 40-70 nm
  - Layer1: rich in Ca, and Zn and very homogenous.
    Small grains 1-3 nm.
  - Layer 2: rich in S and Zn and more heterogeneous.
    bigger grains 3-5 nm.

FY11 Tech Accomplishments: Tribo film analysis





Crystalline phase



Amorphous phase

- LOW FRICTION FILM
- Tribofilm is a mixture of crystalline and amorphous phase.
  - Estimated ratio: 54% amorphous and 46% crystalline phase.
- Total film thickness 100-150 nm.
- Film very rich in Ca and Zn.

FY 11 Tech. progress: Glazing Incidence X ray Diffraction (GIXRD)

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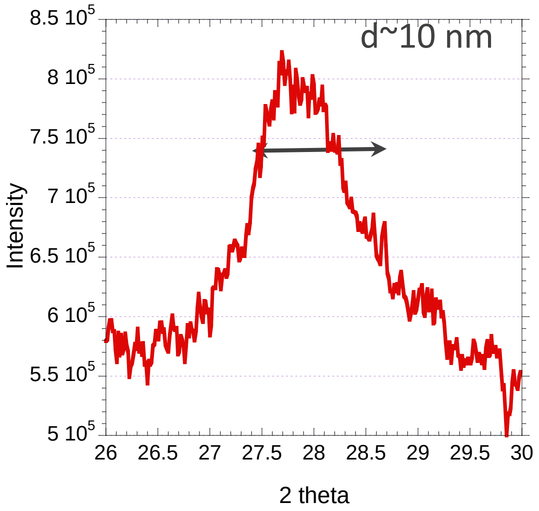
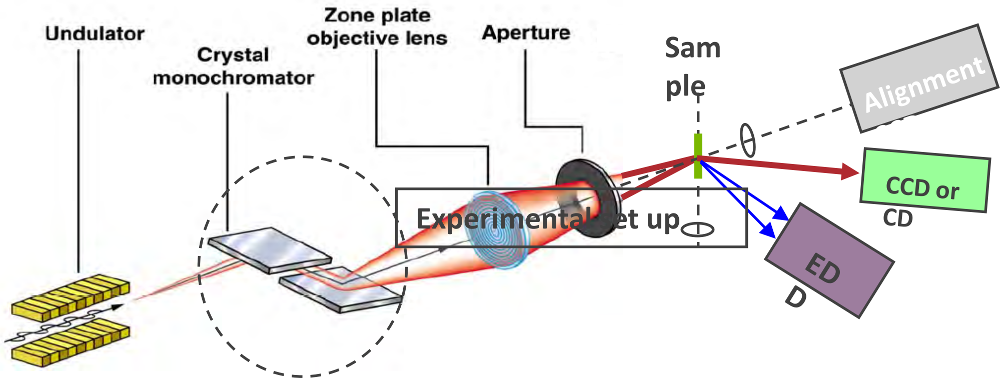
•Conducted at Advance Photon Source (APS)

• Beam 2ID-D

•Operating Conditions: E=10.1 Kev., λ= 1.23 Å





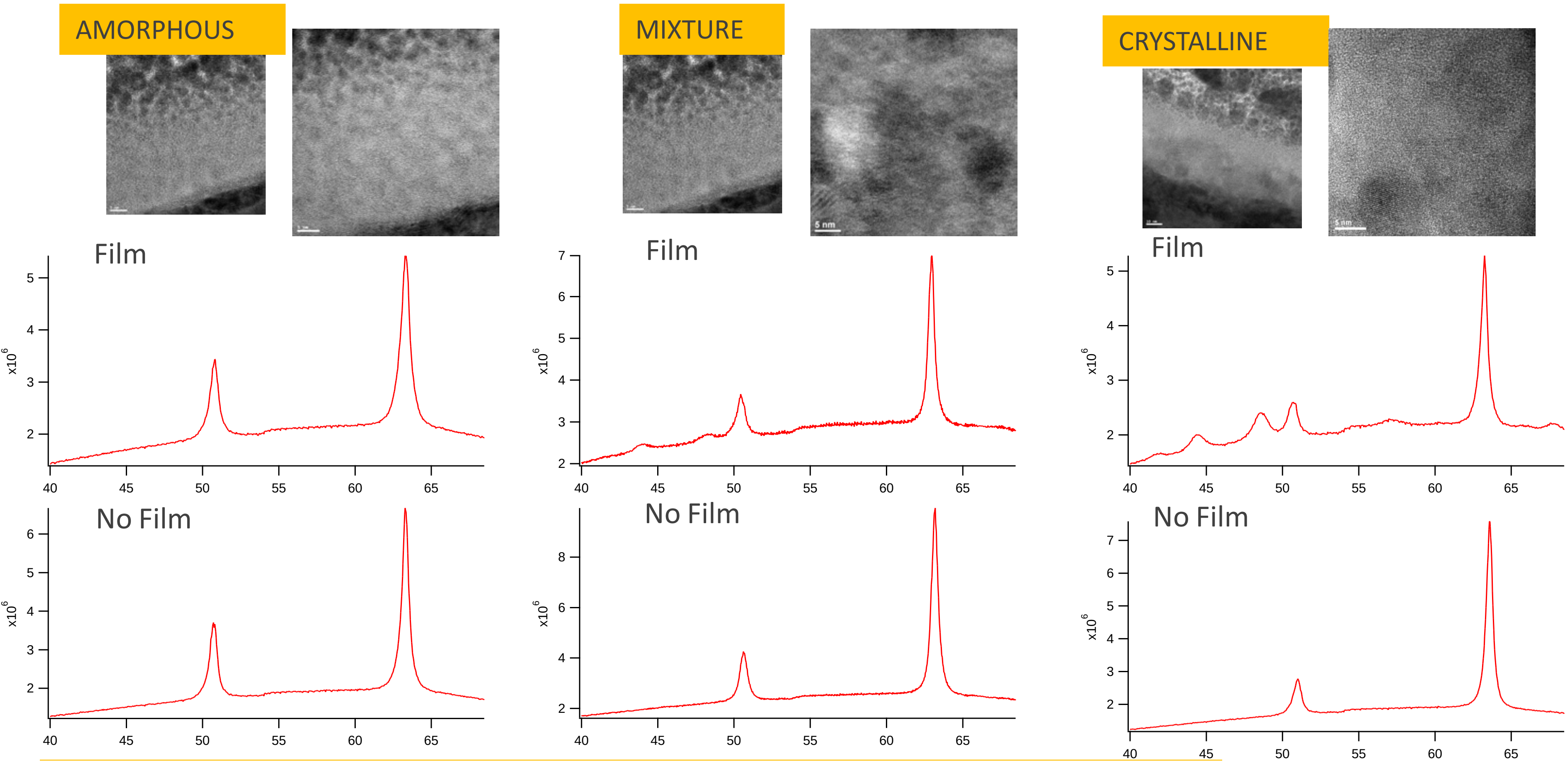
PRELIMINARY HIGHLIGHTS

•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.

FY 11 Tech. progress: Glazing Incidence X ray Diffraction (GIXRD)



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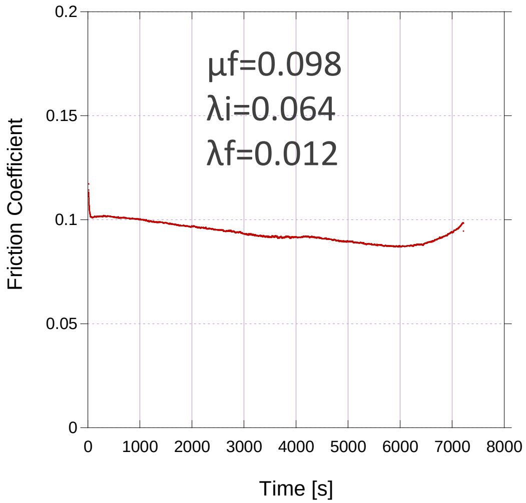
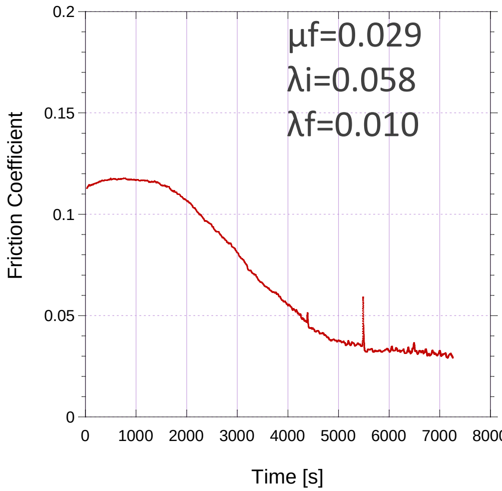
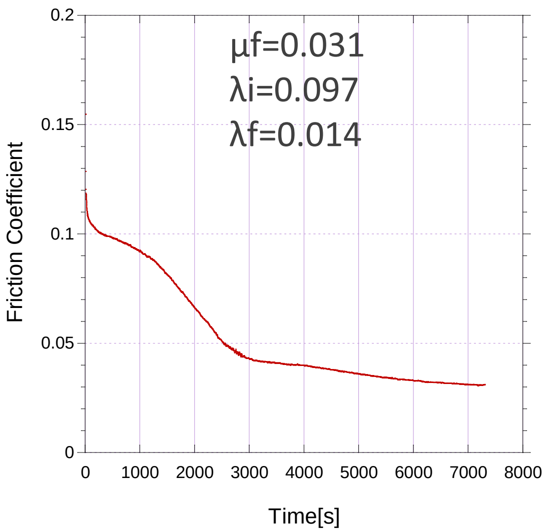
XRD peak indexing to identify crystalline phases in tibo-chemical films

FY11 Tech. Accomplishment - Firm Connection between structure and friction of BF

- With the analysis of about a dozen tribochemical films, a firm connection is established between the structure and friction behavior of the films
  - All crystalline films exhibits consistently higher friction
  - Amorphous or mixture films consistently showed lower friction.
- Based on these finding produced tribochemical films that enable boundary friction as low 0.03 instead of the usual 0.1 to 0.13 values.
  - Significant development in sustainable friction reduction under boundary lubrication regime



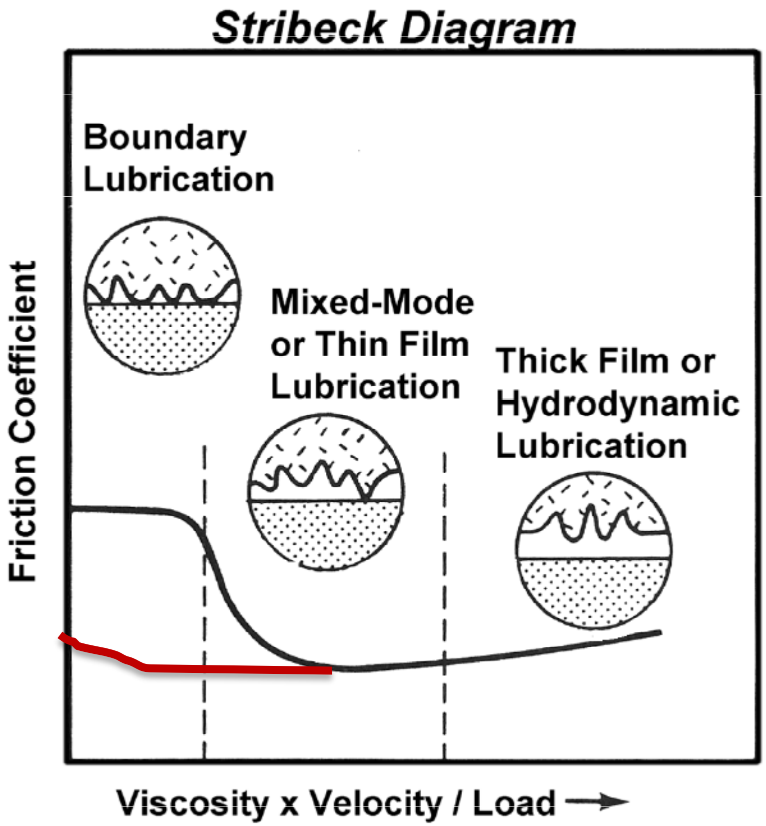




"Take home" point: Sustainable boundary friction reduction achieved via tribochemical film structural modification.

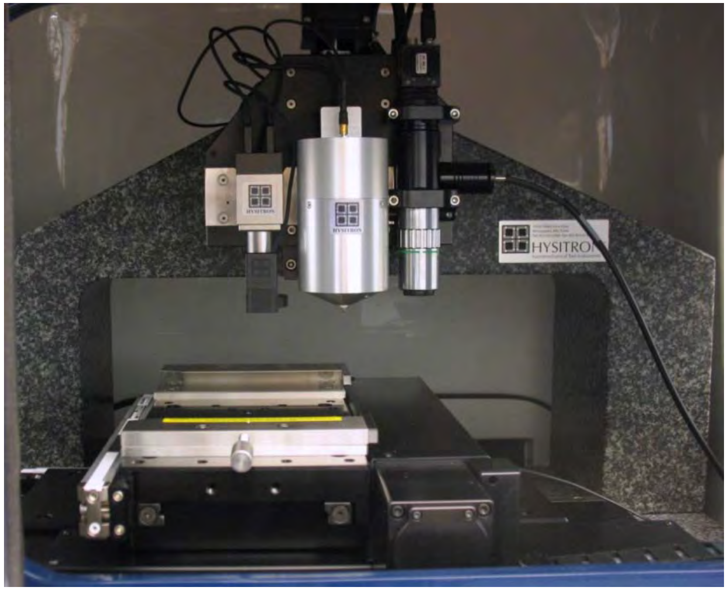
Implication of finding for lubrication regime

- Through tribochemical films structural design and modification, sustainable low-friction boundary regime can be achieved
    - A fundamental modification of the Stribeck diagram.



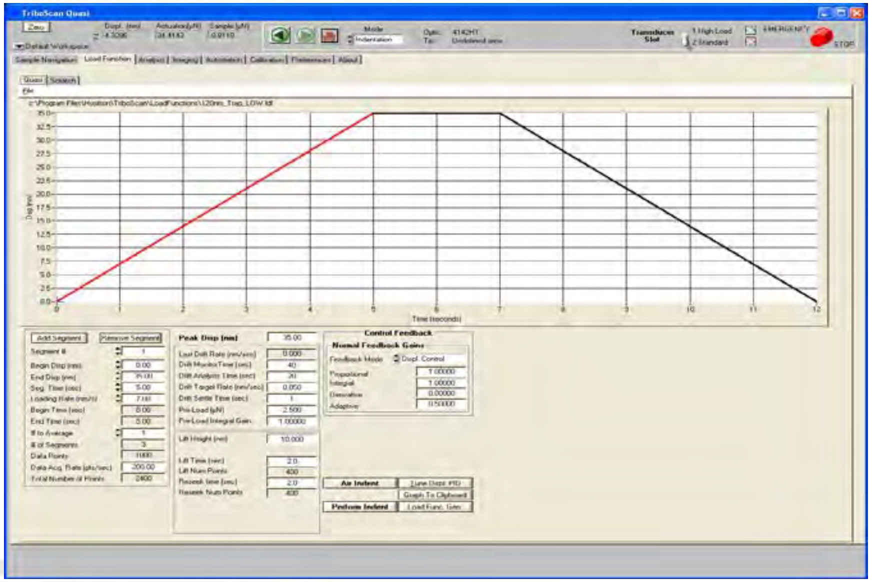
FY11 Tech Accomplishment: Tribo film Mechanical properties

- Nano mechanical properties of several low-friction and high-friction tribo chemical films were determined by instrumented nano-indenter system



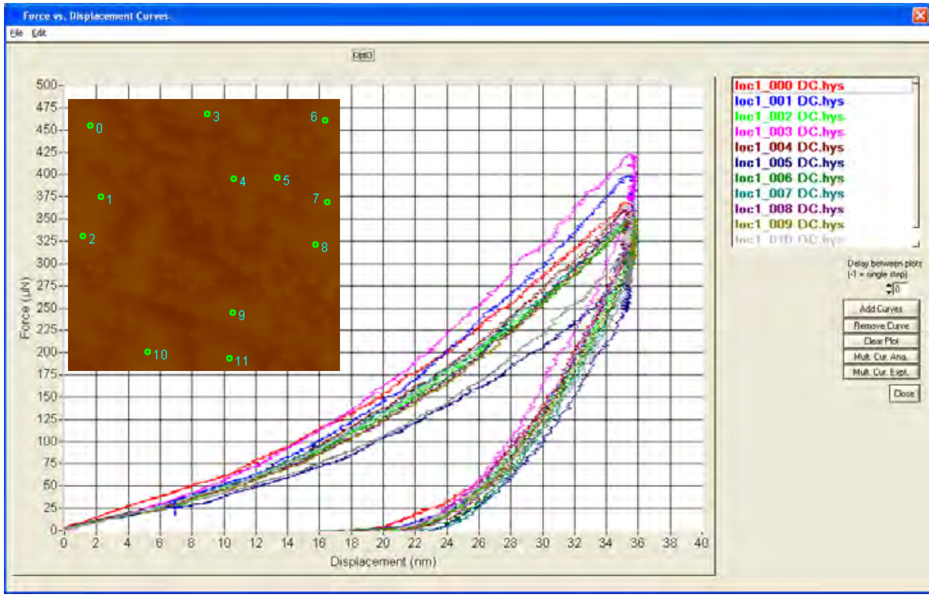
- Tribo film surfaces were first imaged by scanning (AFM) prior to indentation.

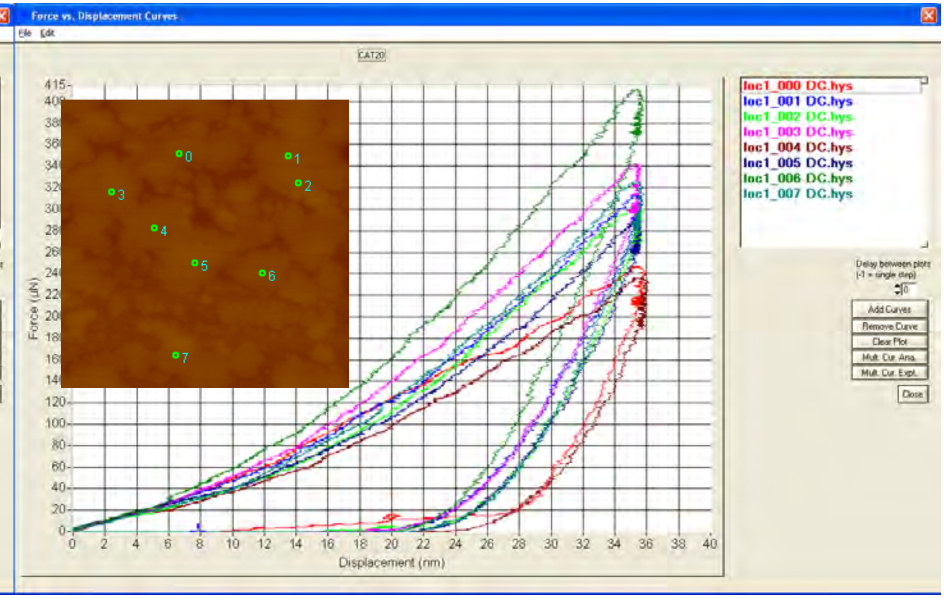
- Hardness and elastic modulus of the films are determined.

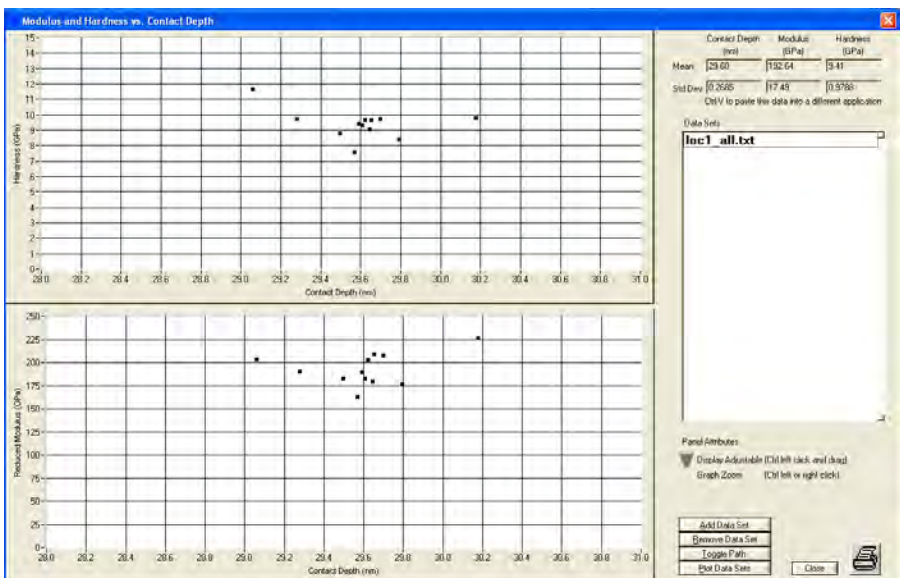


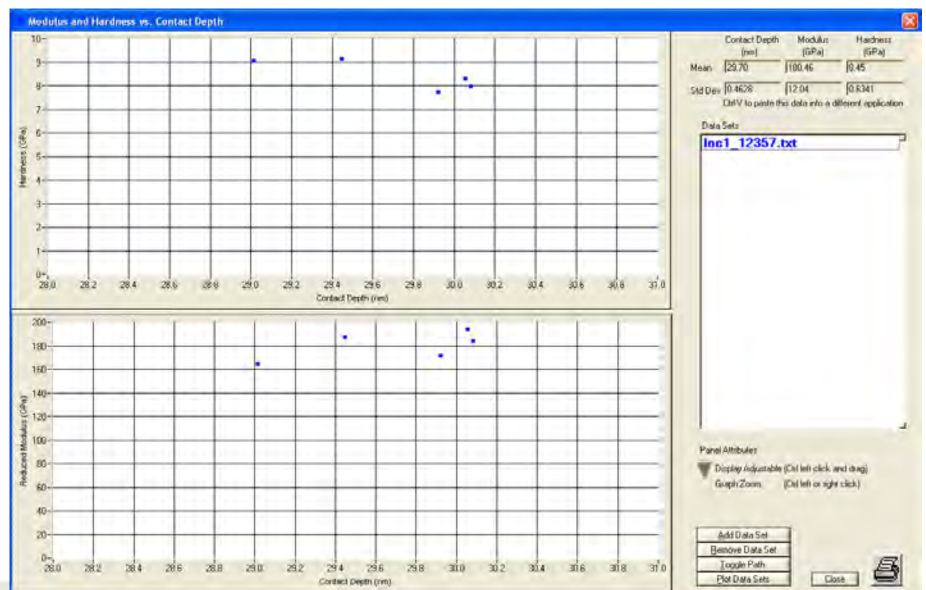
- Mechanical behavior of the film can also be inferred from the load-displacement curve during loading and unloading.

Nano-mechanical properties of Low-friction films

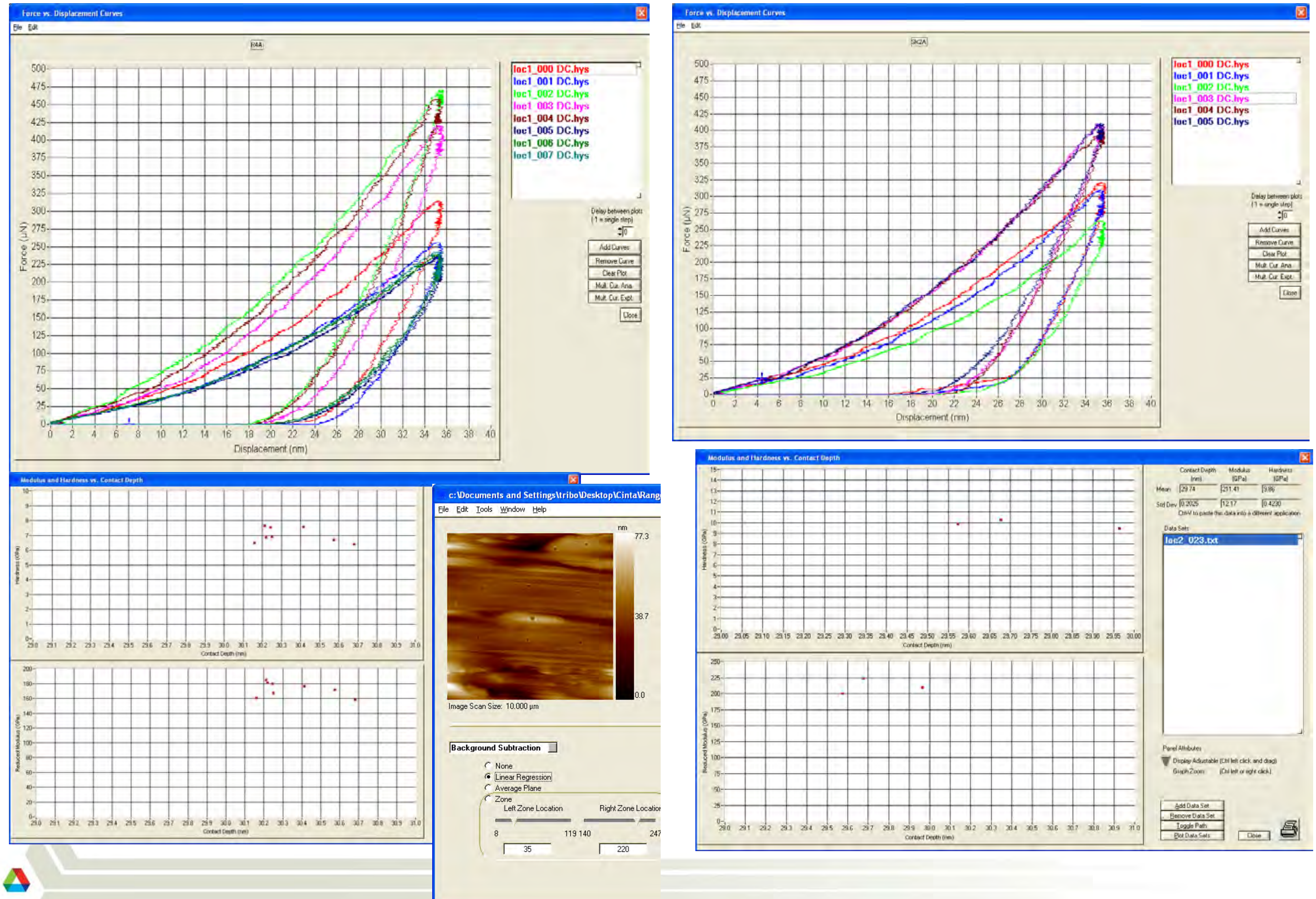






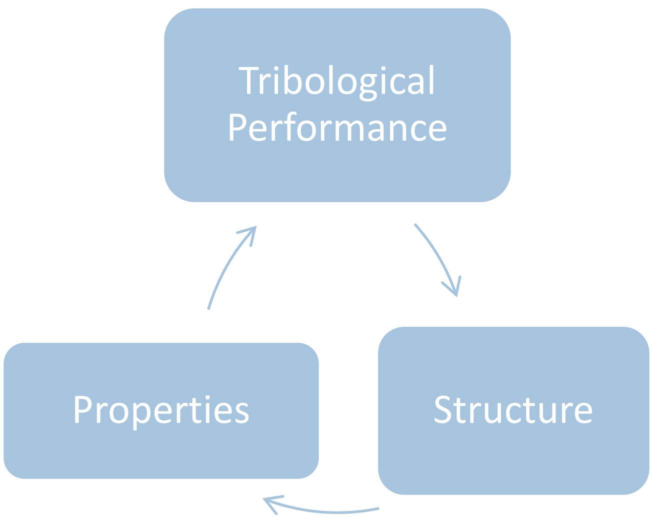


Nano-mechanical properties of higher-friction films



Summary of film Mechanical properties

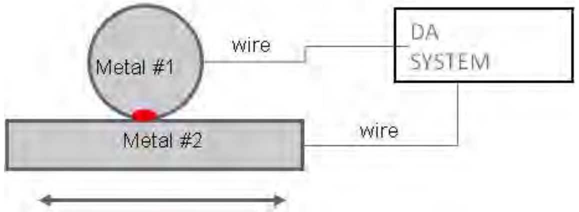
SAMPLE ID		HARDNESS (GPa)	MODULUS (GPa)	FILM ROUGHNESS (nm)
LOW FRICTION		8.45	180.46	20
		9.41	192.64	28
		6.21	130.17	*93*
HIGH FRICTION		7.00	172.56	44
		7.47*	182.28	50

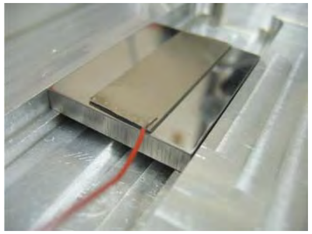


Take home message: Pathway and methodology for tribological performance design of tribo chemical films

FY11 Tech progress: Contact Temperature Measurement

- Thermoelectric approach can be used to assess temperature sliding contact
  - Makes use of electric potential generated as a result Seebeck effect in dissimilar metals in contact with each other at elevated temperature
  - Electric potential generated only at point of touching tips of asperities - essentially instantaneous response time
  - Indicated temperature is average of all asperities in contact at any moment

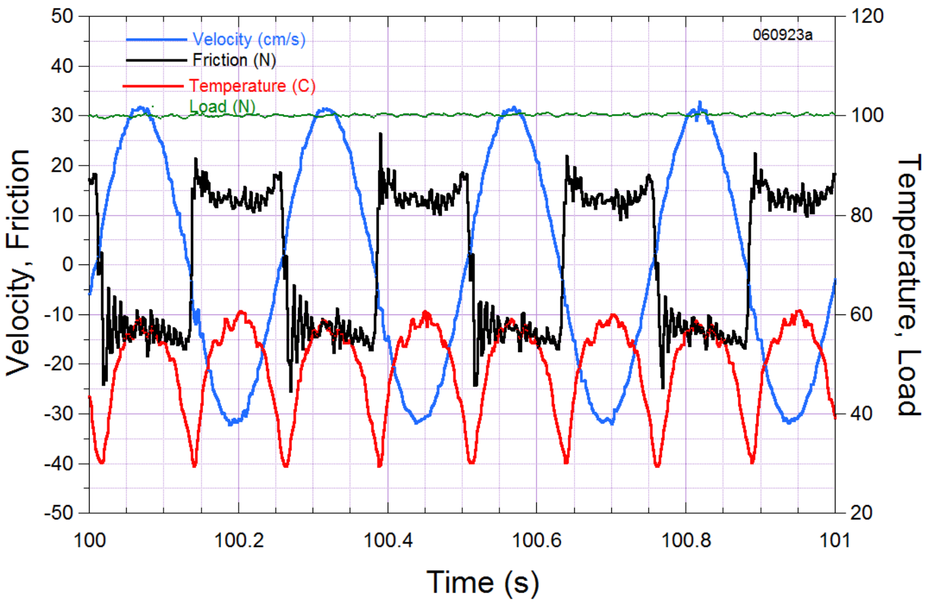




Alumel strip

Chromel strip

- Experimental conditions for first tests
  - Sliding was done in 10W30 engine oil
  - Normal load <100 N to avoid scuffing of nickel-based metals
  - Data acquired at 500 sample/s
  - 1” stroke
  - Couple indicated 22 C at start of test and returned to 22 C after test

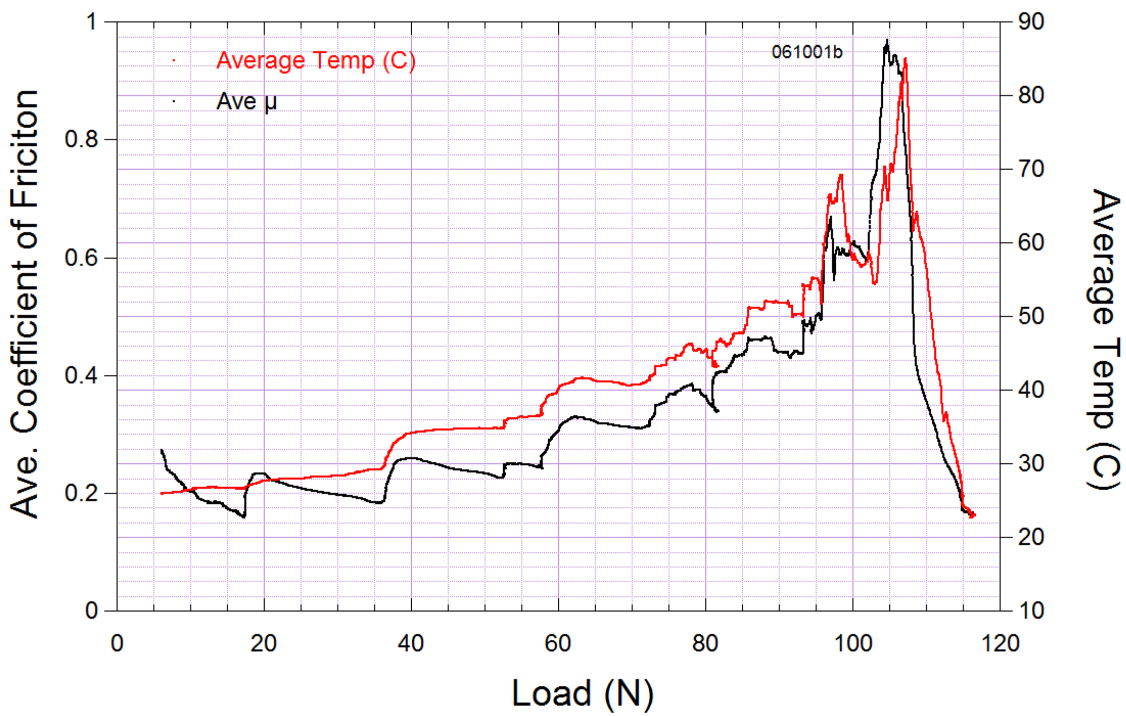


Contact temperature measurement during scuffing test

- Step load protocol
  - Speed – 2Hz
  - Lubricated with PAO 10

- Temperature increases with increasing contact severity

- Instantaneous temperature increase lags friction increase at scuffing
  - Consistent with adiabatic shear instability model for scuffing.



"Take Home" message: A method to measure instantaneous asperity temperature in lubricated sliding under mild and severe contacts developed.

Technical Approach

Project Plan and Structure

Materials

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

Chemical Films

Boundary film formation and loss rate:
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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

Friction modeling approach

- The approach to comprehensive modeling of friction will be based on simultaneous shearing of the three structural elements, i.e. lubricant fluid film, tribochemical boundary film, and the near surface material at a contact patch.

Friction coefficient (μ) = ∑ (shear force for each element)/Normal Force

$$\mu = \frac{F_{sf} + F_{sb} + F_{sa}}{F_N}$$

F_{sf} = Fluid film shear force
F_{sb} = Boundary film shear force
F_{sa} = asperity shear force

- The total friction can be calculate by integration the shear forces of the three elements over the entire contact area as a function of time taking into account contact parameters and surface roughness.

- Develop constitutive equation for the shear behavior of each of the three structural elements.
  - Basis for the eventual development of codes and tools to predict friction in all lubrication regimes.

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.
- **New :** Collaboration to develop a comprehensive friction predictive modeling that involves the three structural elements.

Proposed Future Work.

- **Refine and optimize the methodology for formulation and fabrication of the low-friction tribochemical surface films.**
  - *More work on real contact temperature*

- **Continue 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*
  - *Develop constitutive equation for the tibo-film mechanical behavior for input to the compressive friction modeling effort*
  - *Indication of mechanical failure mechanisms of boundary films*

- **Evaluate the role of surface coatings on the behavior of tribochemical films, especially the low-friction ones.**

- **Continue the development of compressive friction model that includes the three structural elements.**

Summary

- Through detailed analysis and characterization of the structure of tribochemical films, an approach was developed to produce surface films with sustainable 70% reduction in friction under boundary lubrication regimes.

- 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

- A method was developed to measure instantaneous asperity contact temperature during lubricated sliding contact.

Technical Back-Up Slides

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:

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

γ = shear strain

n = work hardening index

ρ = density

C_v = specific heat capacity

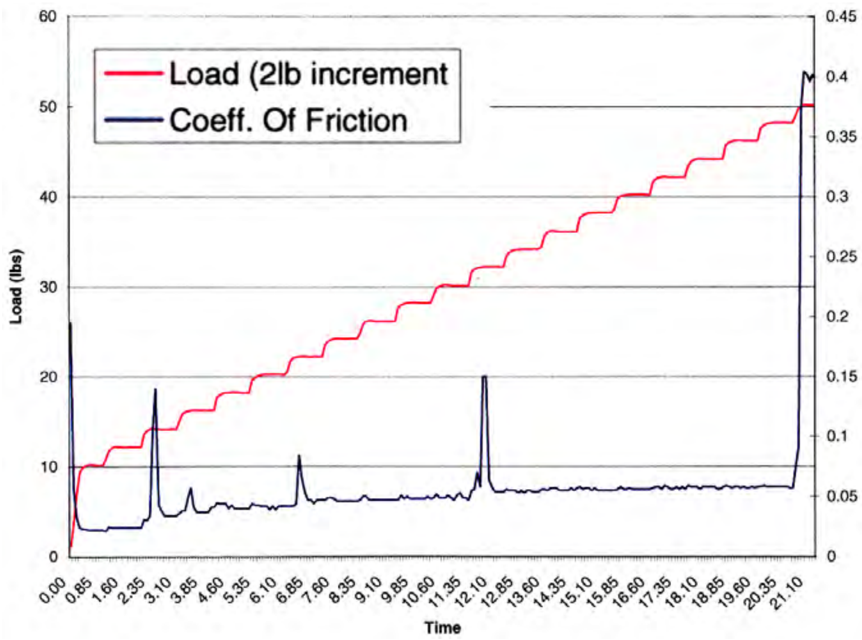
τ = shear strength

T = temperature

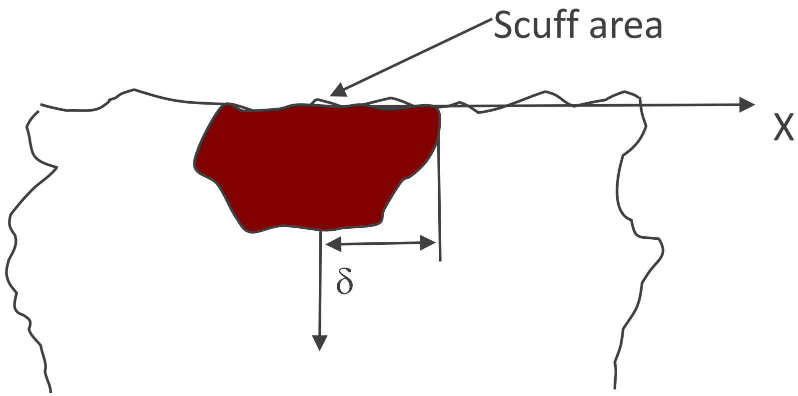
Scuffing Propagation

- After initiation, scuffing may or may not propagates.
  - Micro scuffing
  - Scuff quenching

- Scuffing propagation is governed by a balance between heat generation by the large plastic strain (plastic work) and the rate of dissipation of the heat.
  - If rate of heat dissipation is greater than rate of heat generation, scuffing does not propagate



Scuffing Propagation



β = fraction of plastic work converted to heat (0.9)
τ = Shear stress
λ = Thermal conductivity
γ = Strain rate

Simplified governing equation for scuffing propagation - 1D

Average plastic work rate

Rate of heat conduction across the boundary

$$\frac{d\delta}{dt} = \frac{\dfrac{\beta\tau\dot{\gamma}}{\rho C} - \dfrac{\lambda}{\rho C}\left(\left.\dfrac{\partial^2 T}{\partial X^2}\right|_{\delta} - \dfrac{\partial^2 T}{\partial X^2}\right)}{\left.\dfrac{\partial T}{\partial X}\right|_{\delta}}$$

Velocity of shear instability front

Temperature gradient at boundary