Lubrication Lab Call

Advanced Lubricant Technology – Surface and Lubricant Interactions

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Project ID: FT047

F&L Lubrication Lab Call - Lubricant Technology - *Innovation, Discovery, Design, and Engineering*

Three Thrust Areas, 4 National Labs, Multiple Industrial Partners
Lab Call Project Support for FY17 - $3M @ 75%

- **Thrust I - Surface and Lubricant Interactions**
  - **ANL, ORNL**
- **Thrust II - Technology Innovation, Design & Synthesis**
  - **PNNL, ANL, ORNL**
- **Thrust III - Lubricant Effects on Combustion and Emissions Control**
  - **ORNL, NREL**

Overview: Thrust I

Lubricant and Surface Interactions

Timeline

- Lab Call Lubricant research project supporting DOE/industry lubricant-technologies projects
- October 15, 2016-September 30, 2019
- FY17 - 45% complete

Budget

Project funded by DOE/VT:

FY17: 3M overall; 865K Thrust I (75% level)

Goals/Barriers

- By 2020, develop adequate understanding of lubricant and surface interactions to enable 4% fuel economy improvement goal by:
  - Reducing total engine friction losses by 25%
  - Ensure adequate reliability and durability for engine components with ultra-low-viscosity lubricants.
- GF-5 testing platform

Partners

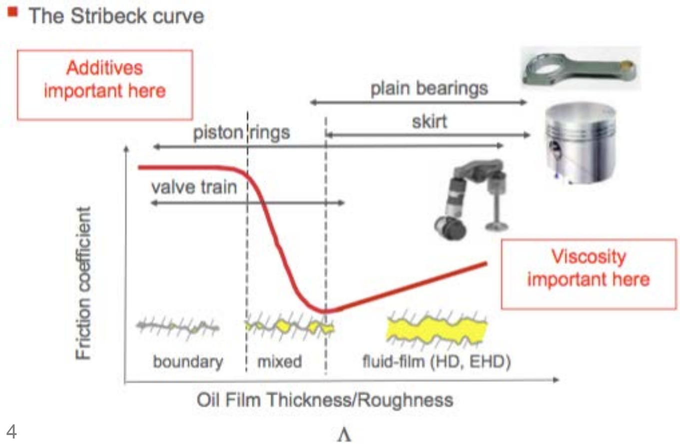
- ANL; ORNL; and multiple Industrial Partners

Introduction to Thrust area I

Rationale and overall approach

- Various analysis and engine test results indicate 10% reduction in total engine friction translates to 0.8 – 1% gain in FE
  - Project goal of 4% increase in FE will require 40-50% reduction in total engine friction.
- Three major systems contribute to engine friction –different lubrication regimes
  - Power cylinder
  - Main bearings
  - Valve train system
- Need to reduce friction in all lubrication regimes

Depending on engine design and operating conditions (duty cycle) contribution to total engine friction:
Hydrodynamic – 80 -90% (viscosity)
Boundary – 10 -20% (additives)



Introduction to Thrust area I

Rationale and overall approach

- Oil viscosity reduction will produce significant reduction in engine friction
  - More contribution from boundary lubrication
  - Component surfaces more vulnerable to wear and scuffing
  - Other issues

- Additive technologies needed to reduce boundary friction and protect the component surface.

- To effectively integrate very low viscosity and functional additive technologies, better understanding and evaluation of the complex dynamic interaction between component surfaces and lubricant is needed.

Thrust I will provide the technical foundation and basis to enable sustainable FEI gains via lubricant technology.

Relevance and Project Objectives

- Relevance:
  - 250 M vehicles – increase in fuel economy of legacy vehicles
  - 10-12 MBBL/day – Reduction; always in national interest
  - 5MMT CO_2/day – Reduction; always a good thing
  - Café 2025 – 55 mpg

- Trust I Specific Objectives: 5 tasks
  - ***Task 1***: Develop rapid, low-cost but effective test protocol to evaluate lubricant technologies connected to real world engine performance.
  - ***Task 2:*** Characterize the tribochemical films from in-use engine components – basis for boundary friction control.
  - ***Task 3:*** Develop mechanistic models for primary failure mode of wear and scuffing in lubricated engine components.
  - ***Task 4:*** Compatibility of lubricant additives with non-ferrous bearing alloys.
  - ***Task 5:*** Evaluate effect of aging and soot on wear performance of engine oils.

- Impact: Accelerate efficient and effective development and deployment of lubricant technologies for FEI gain.

Technical Approach

Specific Tasks

- **Task 1:** Develop a laboratory bench top test techniques to evaluate candidate lubricant technologies focusing on wear and scuffing attributes.
- **Task 2:** Use advanced analytical techniques including FIB/TEM, GIXRD, µXRF to determine the structure of tribo films. Measure nano-mechanical properties and behaviors of tribo films with nano –indentation.
- **Task 3:** Based on extensive failure analysis and characterization of wear and scuffing in engine component, formulate a mechanistic model to form the basis of a predictive simulation model. Validate the predictive model with bench top testing.
- **Task 4:** Experimentally evaluate friction and wear behavior for selected non-ferrous journal bearing alloys lubricated by selected anti-wear and friction modifier additives including mechanistic investigation of the physicochemical interactions between the oil additives and the contact surfaces via surface and tribo film characterization.
- **Task 5a:** Tribological bench testing of friction and wear behavior of sooted oil under boundary conditions. Comprehensive surface characterization to correlate the friction and wear data to the soot and AW chemistry to validate the proposed tribo-corrosion wear mechanism.
- **Task 5b:** Determine the rheological, chemical and physical properties of oil used in engine for different length time. Measure friction, wear and scuffing performance attributes of oil aged for different length of time. Formulate empirical model for properties and performance as a function of ageing time.

FY17 Milestones – Project and Thrust I Specific

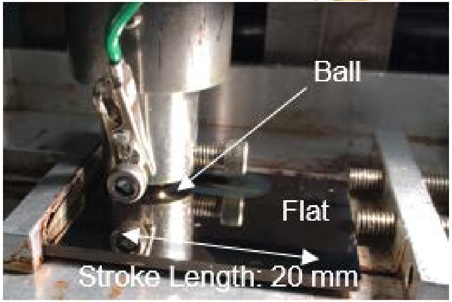
Lab	Task	Description	Date*	Status
ALL		Develop down select criteria, select project baseline lubricant and identify technical pathway to achieve goal	FY17 Q1	completed
ANL	1	Report on protocol conditions and database on baseline oil	FY17 Q4	In progress
ANL	2	Determine structure of tribo films from in-use engine liner component	FY17 Q4	In progress
		Determine nano mechanical properties of tribo film from in-use engine liner	FY17 Q4	In progress
ANL	3	Failure analysis to determine basic mechanisms of wear and scuffing in engine ring and liner components.	FY17 Q4	In progress
		Initiate constitutive predictive formulation for wear and scuffing using the physics-of-failure approach.	FY17 Q4	To start
ORNL	4	Identify wear reduction mechanisms by anti-wear additives for selected non-ferrous alloys	FY17 Q4	In progress
ANL	5	Determine rheological properties variation with time for aged oil Preliminary study of friction and wear with aged oil	FY17 Q4	Just started
ORNL	5	Quantify tribological performance of aged engine oils with correlations to soot and ZDDP contents	FY17 Q4	In progress

* These dates were projected at full funding level; the actual funding is at 75% level, dates will shift

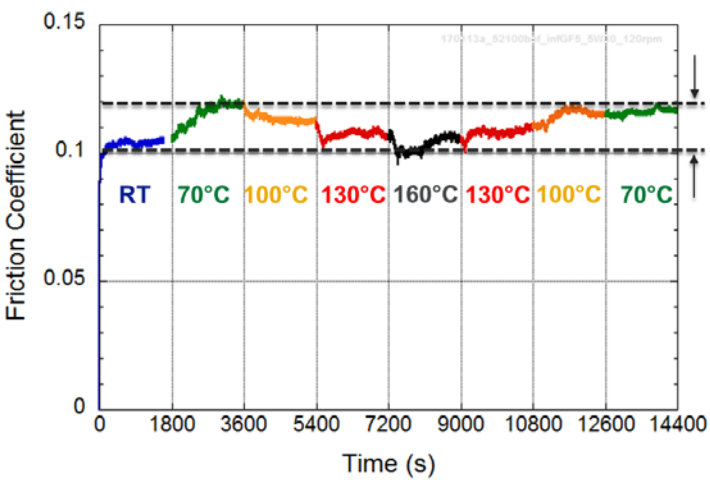
Technical Accomplishments

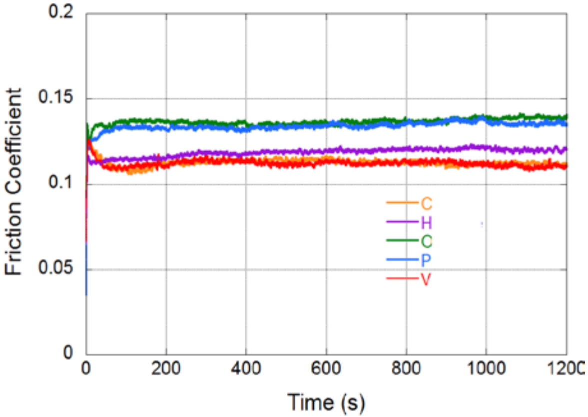
Task 1: Test methodology for rapid evaluation

- Evaluated the friction and wear behavior of 5 commercially available 5W30 GF5 engine oils under boundary lubrication regime.
  - All oils showed boundary CoF of 0.11 -0.14; except for slight difference initially.



- Boundary CoF for project baseline oil was measured at different temperatures.
  - T has minimal effect on CoF

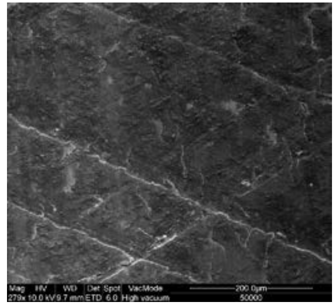




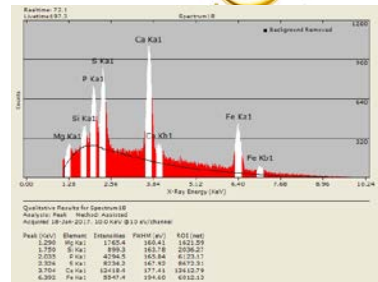
Technical Accomplishments

Task 2: Characterization of Tribochemical films

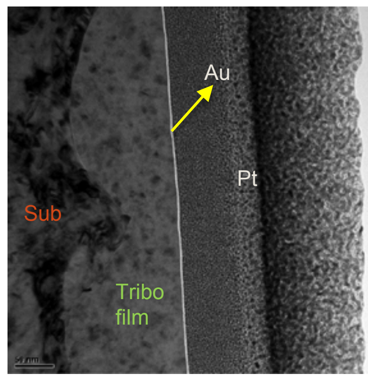
- Used advanced analytical techniques including FIB/TEM, GIXRD, µXRF to determine the structure of tribo films.
- Analysis conducted on engine in-use liner hardware.
  - Provide information on current lubricant technologies in legacy vehicles
- Similar analysis for new lubricant technologies
  - Bench top testing
  - Engine testing



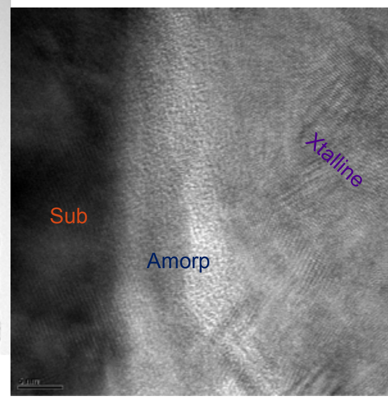
SEM of engine tribochemical film



EDAX of engine tribochemical film

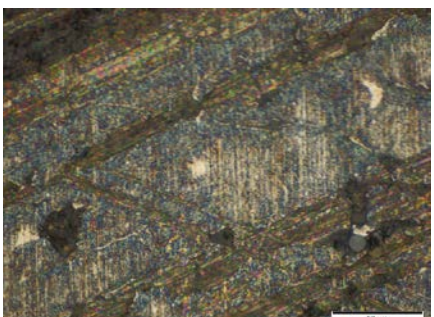


TEM micrograph of tribochemical film



TEM tribo film-substrate interface

Optical micrograph of tribo film



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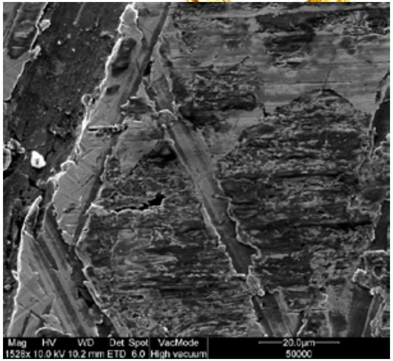
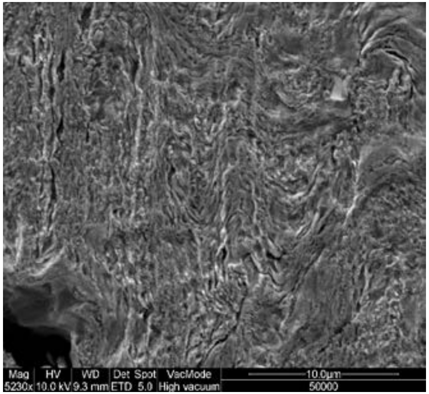
Technical Accomplishments

Task 3: Mechanistic modeling of failure

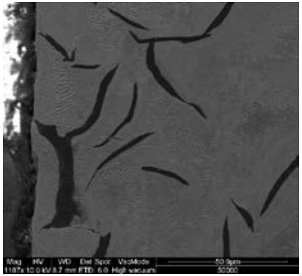
- With ultra-low viscosity oil, engine components will be more vulnerable to wear and scuffing.
- Started mechanistic failure analysis of engine in-use liner hardware – input for mechanistic modeling.
  - Tribochemical films provide protection.
    - Films removal necessary for wear.
  - Artificial removal of tribochemical films showed plastic strain pattern on honing plateau.
  - Subsurface x-section revealed depth of plastic strain.
- Plausible plastic strain-based physic-of–failure wear and scuffing model.
- Initiated conversation with MIT on development of computer model for wear and scuffing based on near-surface plasticity.

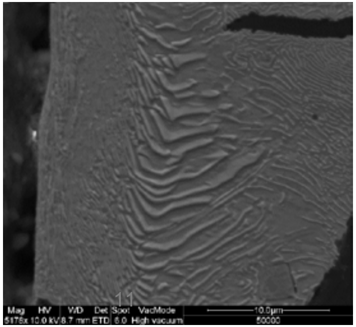


SEM micrograph of wear by removal of tribo film on a honing plateau



Plastic Shear strain pattern on a honing plateau of a liner



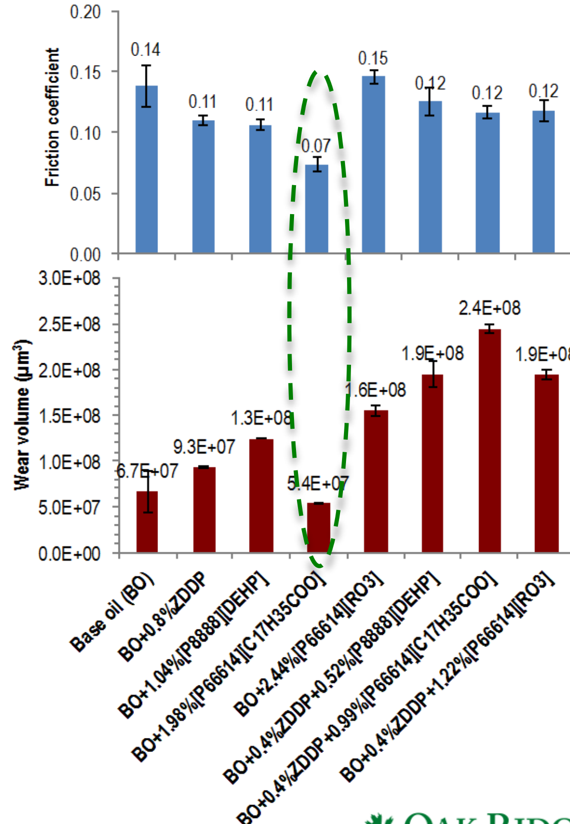


Subsurface plastic deformation from X-section of in-use engine liner

Technical Accomplishments

Task 4: Compatibility of additives with non-ferrous alloy

- Bronze alloy 600 and AW additives
  - ZDDP slightly reduced the friction but made the bronze wear higher! This is opposite to what observed for steel-steel or steel-iron contacts.
  - $[P_{66614}][C_{17}H_{35}COO]$ reduced the friction reduction by ~50% and reduced the wear of bronze by ~20%.
  - $[P_{8888}]$[DEHP] performed similarly to ZDDP with slight friction reduction but increased wear.
  - $[P_{66614}][RSO_3]$ increased both friction and wear.
  - All ZDDP+IL combinations increased the wear of bronze; even $[P_{66614}][C_{17}H_{35}COO]$, the best performer by itself, generated the highest wear when used together with ZDDP.
  - Why some AWs cause higher wear of bronze is being investigated.

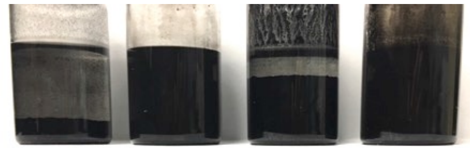


Technical Accomplishments

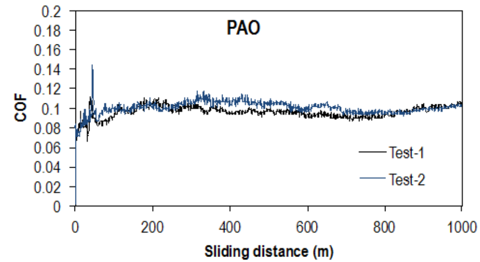
Task 5: Wear mechanisms in sooted oil

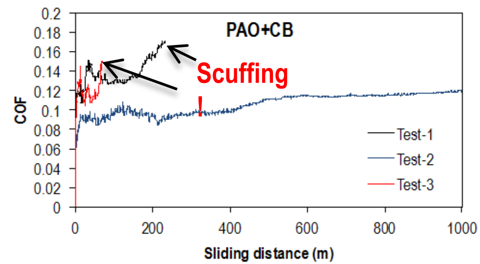
- Suspending carbon black (CB) in oil
  - Soot content in GDTI or diesel engine oils as high as 5% (up to 8% in extreme cases)
  - CB needs surfactant for effective suspension
  - Used 1% PIB dispersant to suspend CB (R250R) at both 1% and 5%.
- Initial tribo-tests at 150 °C showed that CB severely deteriorate the lubricating condition leading to scuffing failure.
  - Results challenged the "soot is abrasive" hypothesis in the literature, since scuffing is associated with severe adhesive wear and, in contrast, abrasive wear often is considered as a competing process.
  - Initial tests were conducted before the PIB dispersant received and tests will be re-done with the surfactant.
- Test matrix has been designed to study the soot's impact in presence of various anti-wear additives.

PAO+1%CB | PAO+1%CB+1%PIB | PAO+5%CB | PAO+5%CB+1%PIB



24 hrs after mixture…





Responses to Previous Year Reviewers' Comments

This project was not reviewed last year.

Collaboration and Coordination

Oak Ridge National Laboratory	In charge of task 4 and task 5a experimental work and activities coordination
Lubrizol	Supplied anti-wear additives for testing and studies at ORNL
Chevron	Supplied base oil for testing and studies at ORNL
Ford	Supplied specimen and aged oil for testing and studies at ANL
Cummins	Supplied drained engine oil with soot for testing and study at ORNL
Infineum	Supplied project base oil and partially formulated fluids for testing and studies at ANL. Also provided engine aged oil
MIT	Working with ANL to develop computer model from mechanistic model
Cytec	Supplied the feed stocks for ionic liquids
Argonne National Laboratory	In charge of tasks 1, 2, 3 and 5b. Coordinator for thrust area I

Remaining Challenges and Barriers

- **Task 1: Test methodology for rapid evaluation**
  - Availability of new technologies to evaluate
  - Correlation of test results with what happens in the engine
- **Task 2: Characterization of tribochemical film**
  - Suitability of engine liner hardware for GIXRD and other x-ray based techniques at APS
- **Task 3: Mechanistic modeling of failure**
  - Wear and damage mode and mechanisms not uniform on liner surface
- **Task 4: Compatibility of additives with non-ferrous surfaces**
  - Mechanistic understanding of the difficulty of forming an anti-wear tribofilm on bronze
  - Compatibility between FMs and bronze and Al-Si alloys
  - Competition of AWs and FMs in interacting with bronze and Al-Si alloy surfaces
- **Task 5: Oil aging and performance degradation**
  - Deconvolution of oil aging mechanisms in engine
  - Role of ZDDP in the wear process and wear rate in sooted engine oils

Proposed Future Work

- **Task 1: Test methodology for rapid evaluation**
  - Friction and wear testing under different contact conditions with ring and liner specimens.
  - Evaluation of the lubricant technologies developed in the project.
- **Task 2: Characterization of tribochemical film**
  - Continue characterization of tribochemical films from engine in-use components.
  - Measurement of nano-mechanical properties and behavior of tribochemical films by nano-indentation and nano-scratch techniques.
- **Task 3: Mechanistic modeling of failure**
  - Continue failure analysis of in-use engine ring and liner parts – database.
  - Develop a technique to quantify the strain patterns on liner near-surface region.
  - Initiate a strain-based wear and scuffing model/constitutive equation.
- **Task 4: Compatibility of additives with non-ferrous surfaces**
  - Mechanistic understanding of the difficulty of forming an anti-wear tribofilm on bronze.
  - Compatibility between FMs and bronze and Al-Si alloys.
  - Competition of AWs and FMs in interacting with bronze and Al-Si alloy surfaces.
- **Task 5: Oil aging and performance degradation**
  - Deconvolution of oil aging mechanisms in engine.
  - Role of ZDDP in the wear process and wear rate in sooted engine oils.

Any proposed future work is subject to change based on funding levels

Summary

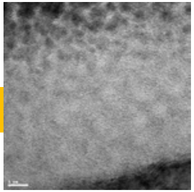
- As part of a larger project to develop lubricant technologies to enable 4% gain in FEI, thrust I focus is providing technical foundation for low-friction and surface protection through controlled interaction with lubricant.
  - A cost-effective and rapid test methodology is being develop to screen potential lubricant technologies.
  - Characterization of the structure and properties of tribochemical films from current in-use engine component will enable development and adaption of lubricant technologies for legacy vehicles.
  - Based on analysis of in-use engine parts, a physics-of-failure approach from near-surface material plastic strain is emerging. When fully developed, will enable adequate reliability and durability for engine operating with ultra-low viscosity oil.
  - Evaluation of oil additives compatibility with non-ferrous engine component is important. ZDDP fails to protect bronze and a carboxylate IL seems to work very well. Wear could be severely increased when a wrong additive is used.
  - Soot in oil may not be as abrasive as often assumed. An alternative mechanism based on tribo-corrosion is under investigation
  - Impact of engine oil aging on friction and surface protection as a function of time is underway.

Backup Slides

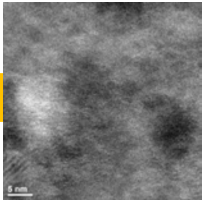
Technical Accomplishment

Task 2: GIXRD of tribo-chemical film

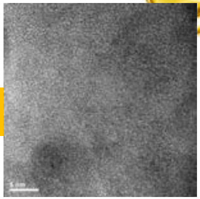
AMORPHOUS

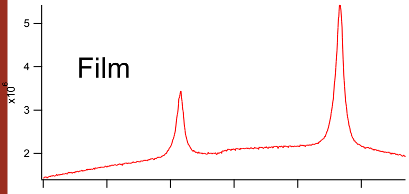


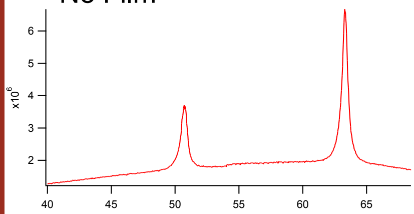
MIXTURE

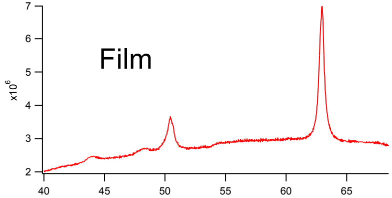


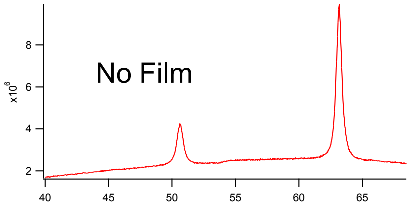
CRYSTALLINE

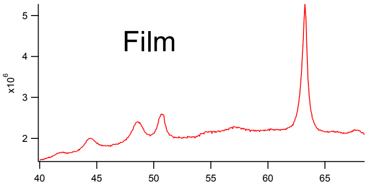


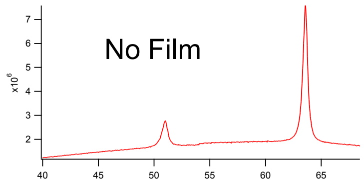


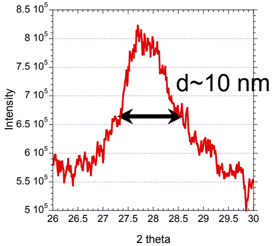












HIGHLIGHTS

•Broad peaks of tribo-film. indicative of nano-size of grains

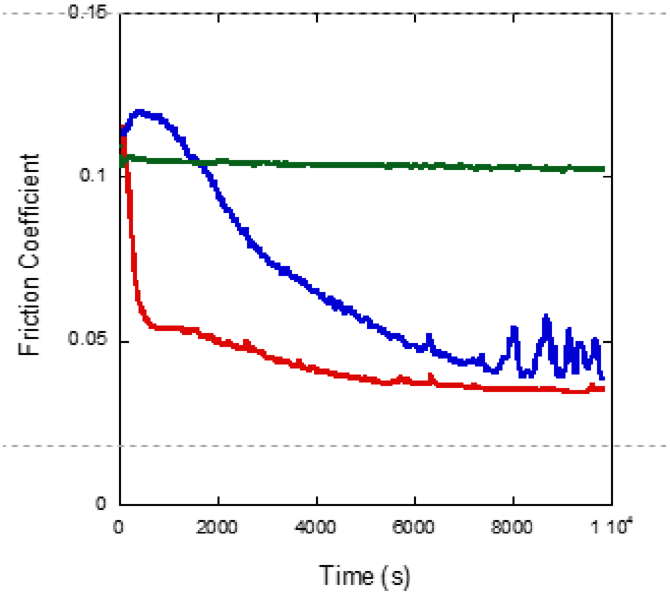
•Indication of some amorphous layer by the reduction of

•So far, results from X-ray analysis are consistent with TEM

Technical Accomplishments

Task 2: Correlation between structure and behavior of tribo-chemical films

- Based on analysis of several 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.



- Durability of films observed to depend on structure of tribochemical film.

Technical Accomplishment

Task 4: Compatibility of additives with non-ferrous bearing alloys

- Compatibility between AWs and A380 Al alloy
  - ZDDP was effective in wear protection for the A380 Al-Si alloy.
  - $[P_{8888}][DEHP]$ and $[P_{66614}][C_{17}H_{35}COO]$ also performed well, but not effective as ZDDP.
  - $[P_{66614}][RSO_3]$ caused a dramatic wear increase by two orders of magnitude!
  - Performance of ZDDP+IL combination was totally unpredictable from their individual behavior.
    - ZDDP+$[P_{8888}][DEHP]$ → protective
    - ZDDP+$[P_{66614}][C_{17}H_{35}COO]$ → destructive
    - ZDDP+$[P_{66614}][RSO_3]$ → protective
  - A tribo-corrosion hypothesis is proposed and characterization is being performed to seek fundamental understanding.