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Low-Friction Engineered Surfaces

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Ricardo: *James Kezerle and Lee Oberto*
UMich: *Zoran Filipe*

DEER 2007: Diesel Engine-Efficiency and Emissions Research (DEER) 2007 Conference

Detroit, Michigan

August 12-16, 2007

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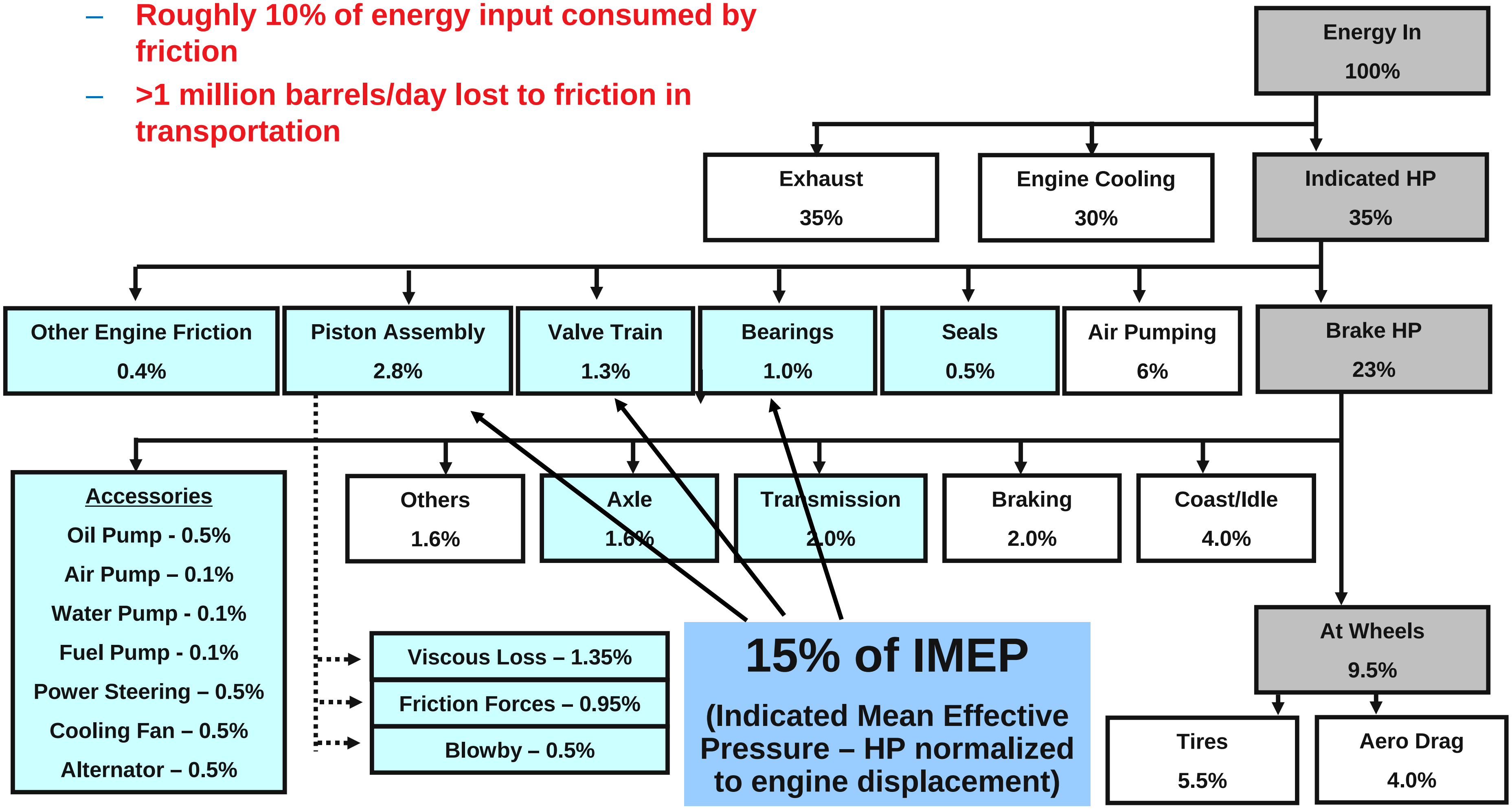
Role of Friction & Wear in Vehicles

- Traditionally, the role of friction and wear in transportation has addressed issues associated with reliability and durability – engineering the tribological system (consisting of lubricants & additives, materials & coatings, and component geometry/finish) to improve component lifetime and mitigate catastrophic failure (e.g. scuffing)
  - Changing environments continue to challenge the ability of current tribological systems (low-lubricity fuels, low SAPS lubricants, greater loads, EGR, etc.)
- Increasing fuel prices, tighter emission standards, and concerns over global warming gases are now driving researchers worldwide to develop more efficient tribological systems to reduce parasitic friction losses.
  - More energy is lost to friction than is delivered to the wheel. Approximately 10 % of the fuel consumed in transportation is lost to friction in the engine. Another 6% is consumed by friction in the driveline

- Fuel savings in the range of 3-5 % can be achieved by reducing parasitic engine losses, while another 2-4 % can be saved by reducing parasitic driveline losses

More Energy is Lost to Friction Than Delivered to the Wheel

- Energy Map- Passenger Vehicle EPA Cycle
  - Roughly 10% of energy input consumed by friction
  - >1 million barrels/day lost to friction in transportation



Energy In 100%

Exhaust 35%

Engine Cooling 30%

Indicated HP 35%

Other Engine Friction 0.4%

Piston Assembly 2.8%

Valve Train 1.3%

Bearings 1.0%

Seals 0.5%

Air Pumping 6%

Brake HP 23%

Accessories
Oil Pump - 0.5%
Air Pump – 0.1%
Water Pump - 0.1%
Fuel Pump - 0.1%
Power Steering – 0.5%
Cooling Fan – 0.5%
Alternator – 0.5%

Others 1.6%

Axle 1.6%

Transmission 2.0%

Braking 2.0%

Coast/Idle 4.0%

Viscous Loss – 1.35%

Friction Forces – 0.95%

Blowby – 0.5%

15% of IMEP

(Indicated Mean Effective Pressure – HP normalized to engine displacement)

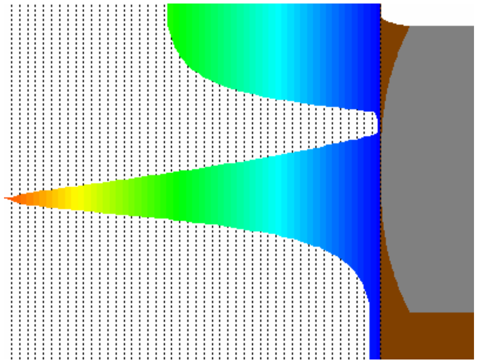
At Wheels 9.5%

Tires 5.5%

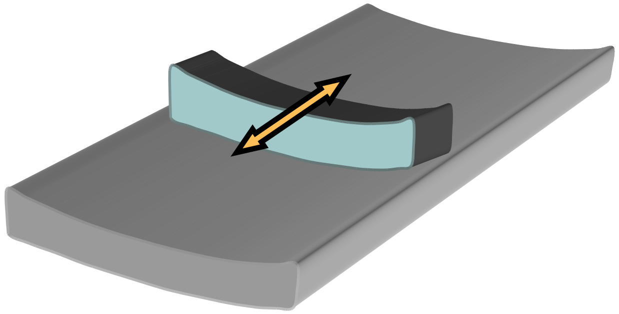
Aero Drag 4.0%

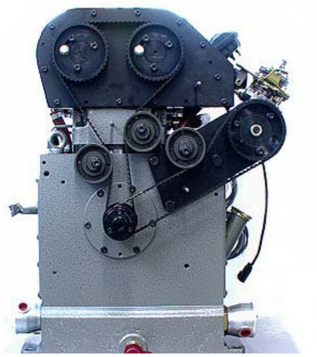
Strategy of Parasitic Friction & Wear Research

- Develop and Apply Mechanistic Models of Friction (Boundary and Viscous) Losses to Predict Parasitic Losses as a Function of Engine Conditions (Load & Speed), and Tribological Conditions (Boundary Friction and Oil Viscosity)
  - Scale fuel consumption as a function of FMEP and IMEP for a prototypical HD diesel engine
  - Predict the impact of low-friction (boundary-layer friction) and low-viscosity lubricants on fuel economy
- Evaluate/Screen the Potential of Candidate Surface Treatments and Additives to Reduce Boundary Friction Under Lab Conditions Prototypical of Engine Environments
  - Benchtop friction tests using prototypical engine components
  - Impact of materials, coatings, surface texture, and lubricant additives and viscosity
- Validate Codes/Models and High-Potential Solutions in Fired Engines Using In-Situ Friction Measurement Techniques



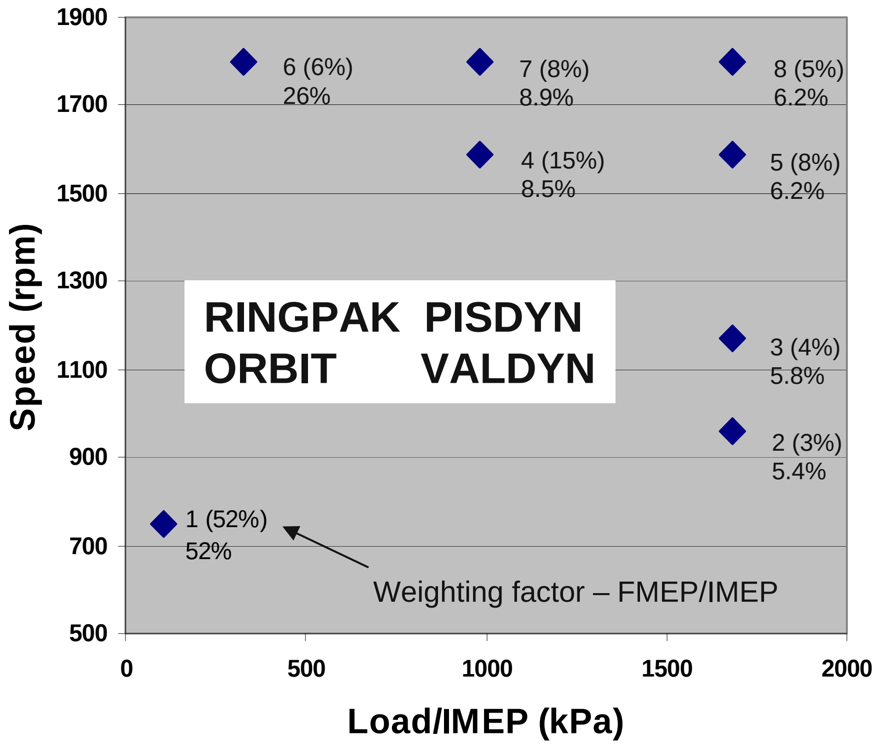
RINGPAK
PISDYN
ORBIT
VALDYN

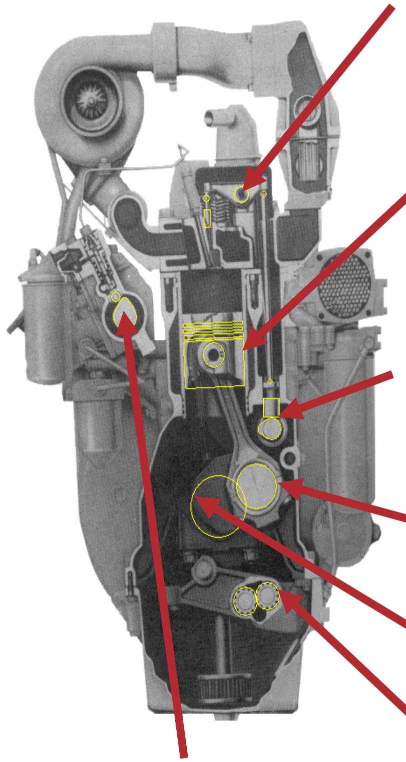




Integrated Mechanistic Models to Predict Impact of Low-Friction Surfaces and Low-Viscosity Lubricants on Parasitic Energy Losses (FMEP) and Fuel Economy

- FMEP calculated at 8 different modes and weighted to predict effect on fuel consumption for a HD driving cycle





- **Rocker bushing ***
- **Rocker tip to valve ***
- **Pushrod to rocker interface ***

- **Piston pin bearing ***
- **Rings ***
- **Piston Skirt ***

- **Cam - follower interface ***
- **Cam bearings ***
- **Follower - pushrod interface ***
- **Timing drive**

- **Journal bearings**
- **Crankshaft windage**

- **Crankshaft main bearings**
- **Main seals ***

- **Oil Pump**

- **Fuel injection system**

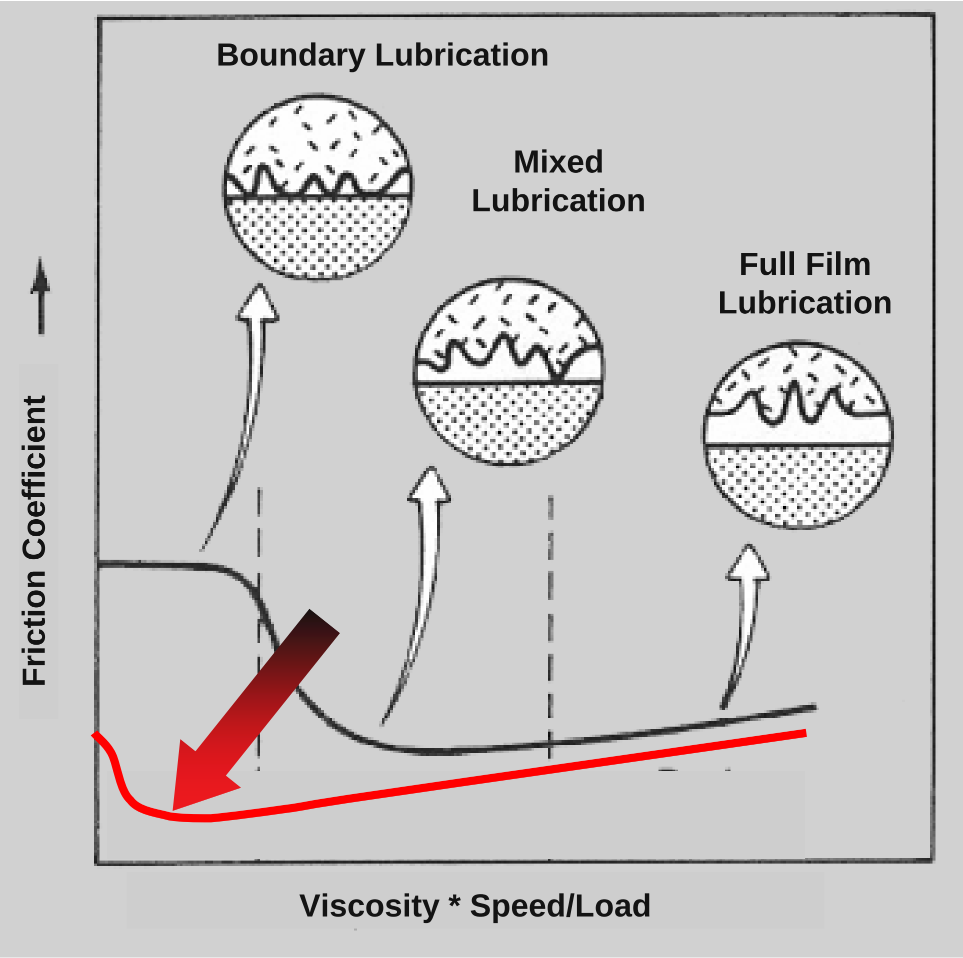
*** interface considered in current study**

$$\text{FCSF} = \frac{\text{IMEP} + \Delta\text{FMEP}}{\text{IMEP}}$$

(Fuel Consumption Scaling Factor)

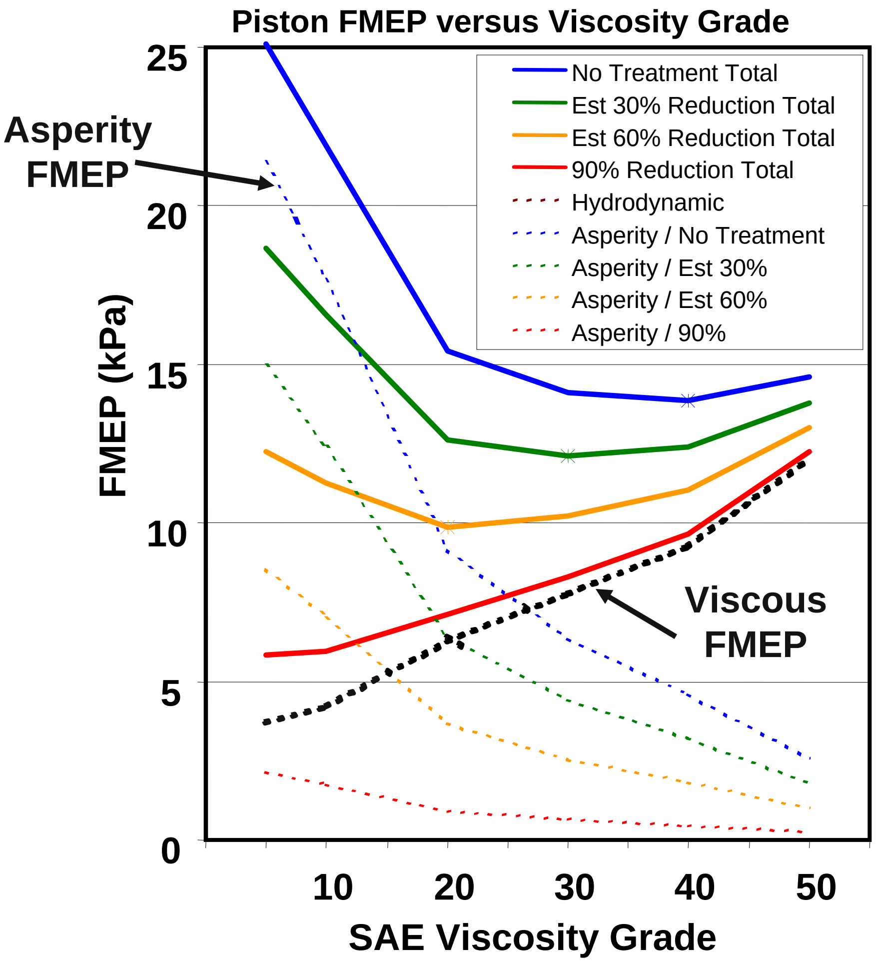
Role of Boundary and Hydrodynamic Lubrication Regimes - Tribological System

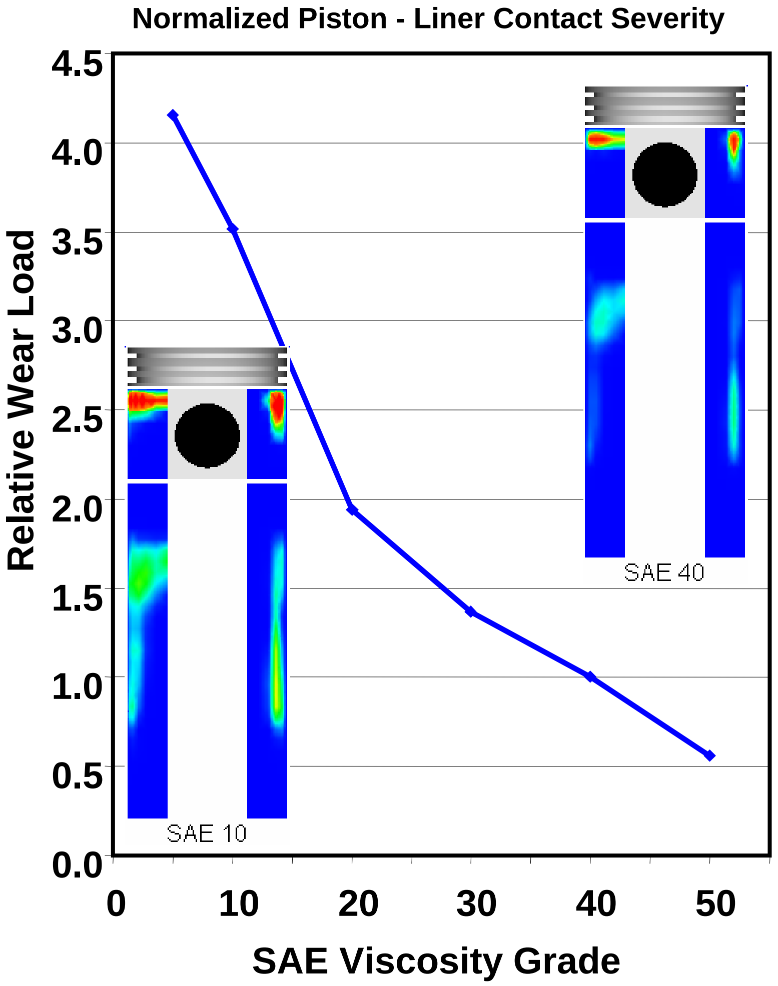
- Different regimes of lubrication depending on the degree of contact between sliding surfaces
- Boundary lubrication characterized by solid-solid contact – asperities of mating surfaces in contact with one another
- Contrast boundary lubrication with full-film lubrication in which mating surfaces are separated by a film.
- In between, mixed lubrication occurs.



Boundary and Hydrodynamic Friction: Model Impact on FMEP and Wear Severity

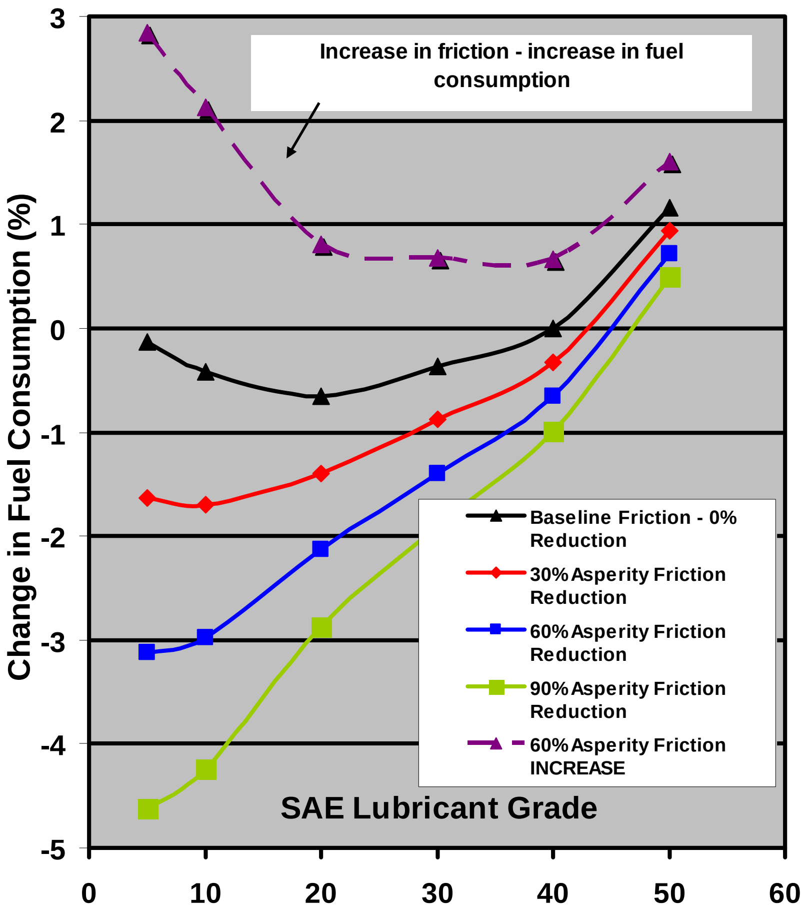
- Total FMEP is the sum of the Asperity friction and the hydrodynamic friction
  - Boundary FMEP decreases with increasing lubricant viscosity – shifting from BL to ML regime
  - Hydrodynamic FMEP increases with increasing viscosity

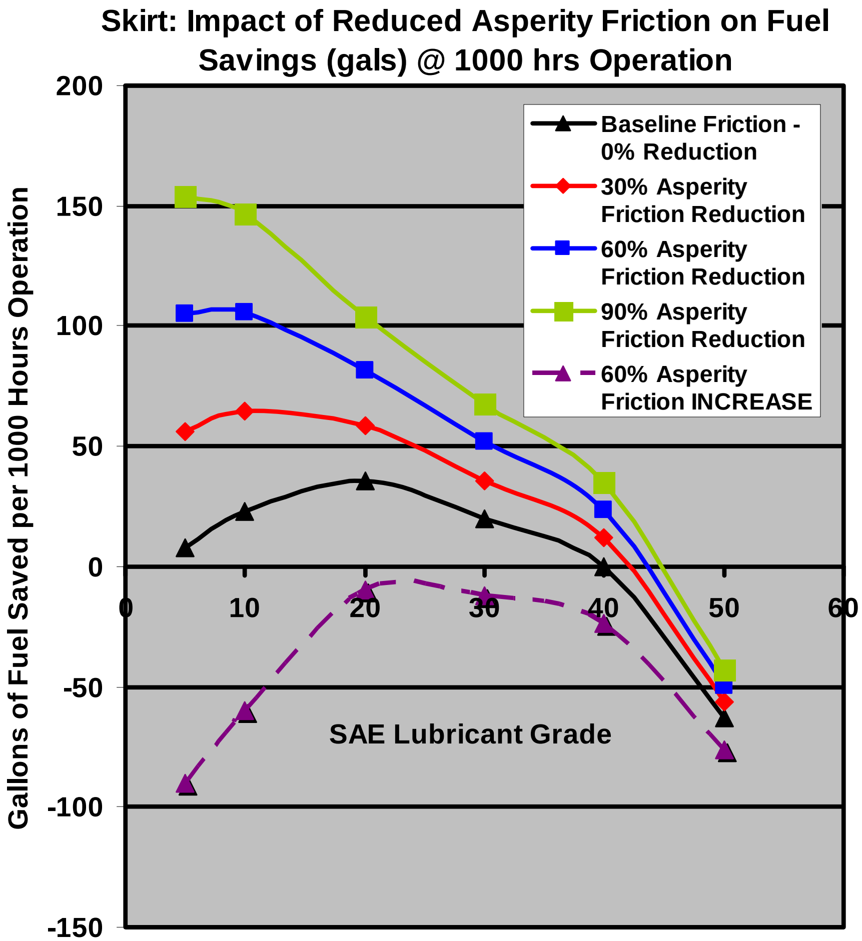

Piston FMEP versus Viscosity Grade


Normalized Piston - Liner Contact Severity

Low-Friction (Boundary-Friction) Surfaces Enable Use of Low-Viscosity Lubricants to Provide Fuel Savings up To 5%

- Low Boundary Friction Only – up to 1% savings
- Low Boundary Friction AND Low Viscosity – 3-5 % savings
- Estimates of Payback on Technology



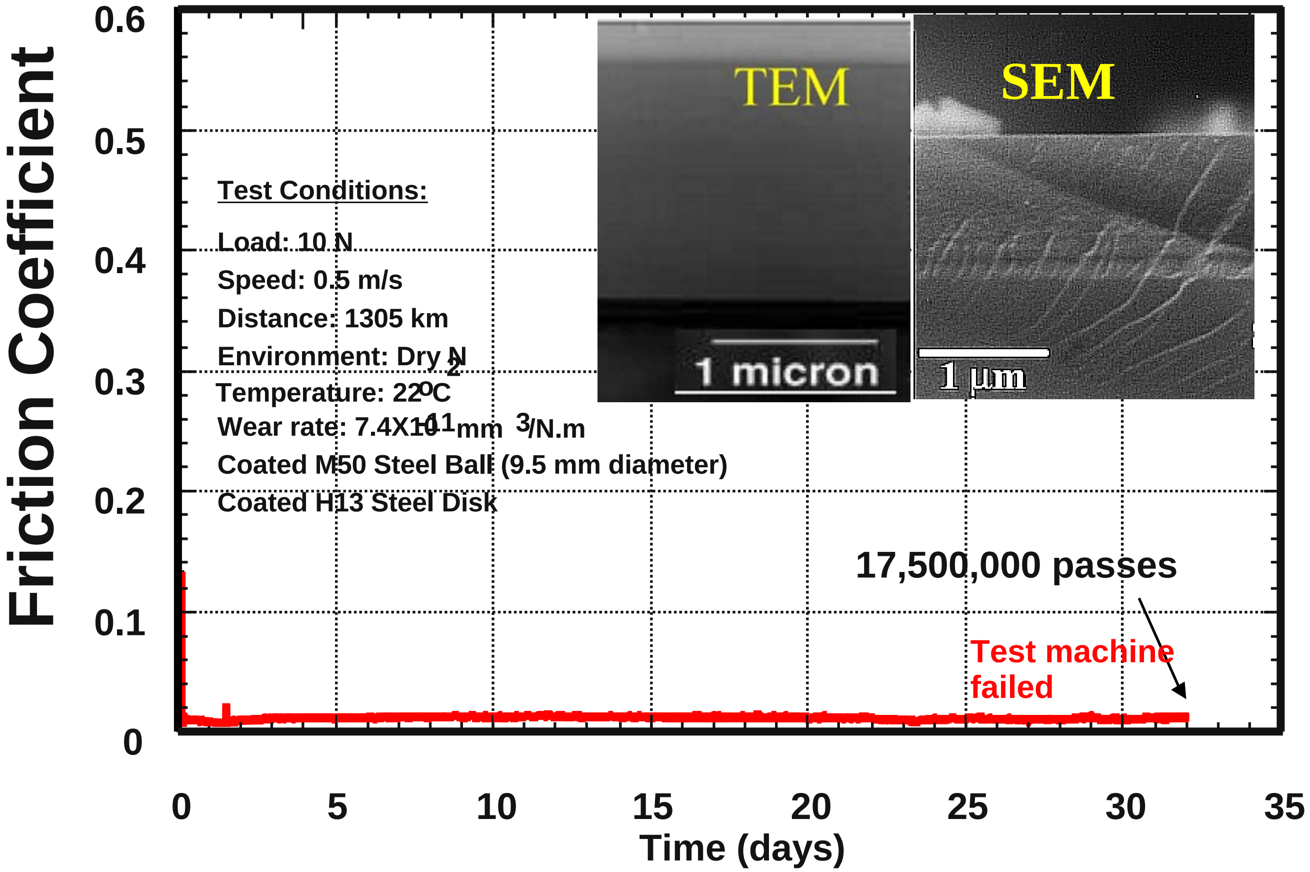

Skirt: Impact of Reduced Asperity Friction on Fuel Savings (gals) @ 1000 hrs Operation

Identifying Low-Friction Technologies that Enable Low-Viscosity Lubricants and Maintain Durability/Reliability

- Measurement of friction using benchtop tribometers providing data on the potential of advanced engineered surfaces and lubricants to provide low-friction tribological systems
  - Benchtop test configurations
    - *Unidirectional Sliding*
      - Pin-on-Disc
      - Block-on-Ring
    - *Reciprocating Sliding*
      - Ring-on-Liner
  - Candidate low-friction technologies
    - *Coatings (Amorphous carbon, Superhard nanocomposites, Commercial Coatings – CrN, E-NiB …)*
    - *Lubricants (Additives – formation of low-friction boundary films)*
    - *Textured surfaces*

Near Frictionless Carbon Films

- **Non-crystalline structure**
  - a-C:H
- **Near RT process**
  - Ceramics, metals, polymers
- **Ultra-low friction**
  - < 0.001
- **Reduced Wear**
  - 10^5 lower



Test Conditions:

Load: 10 N

Speed: 0.5 m/s

Distance: 1305 km

Environment: Dry N_2

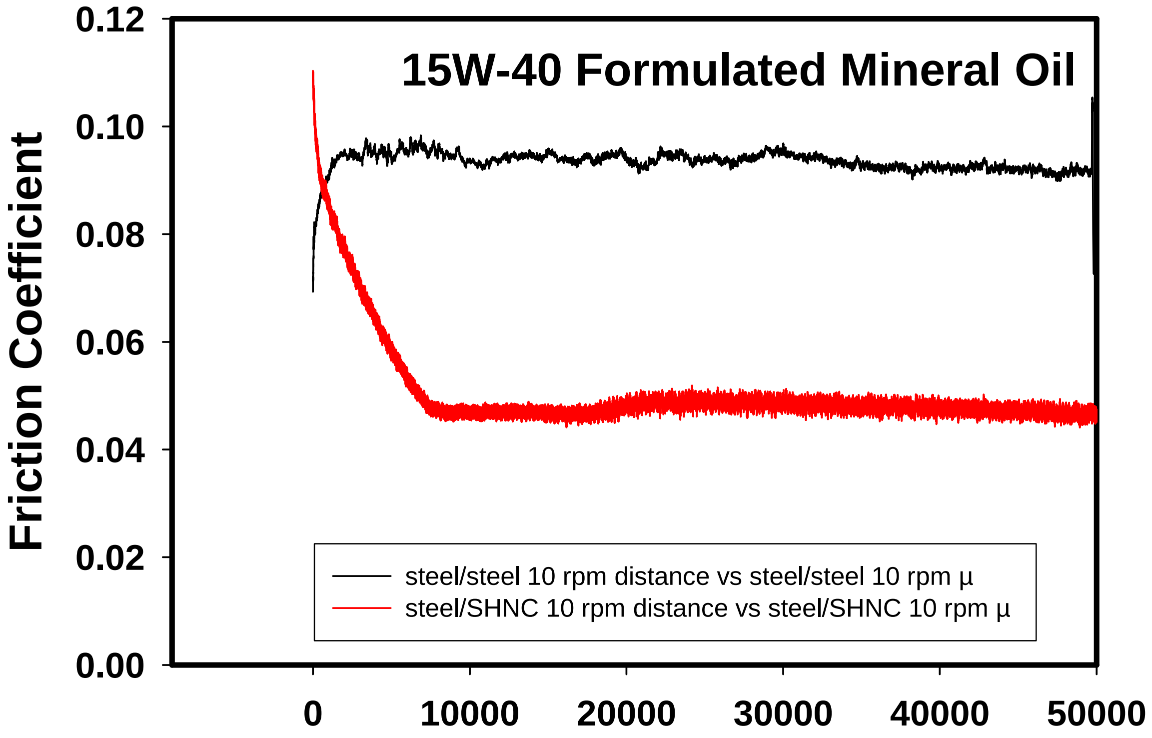
Temperature: 22^{o}C

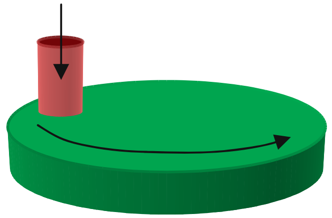
Wear rate: 7.4X10^{-11} mm^3/N.m

Coated M50 Steel Ball (9.5 mm diameter)

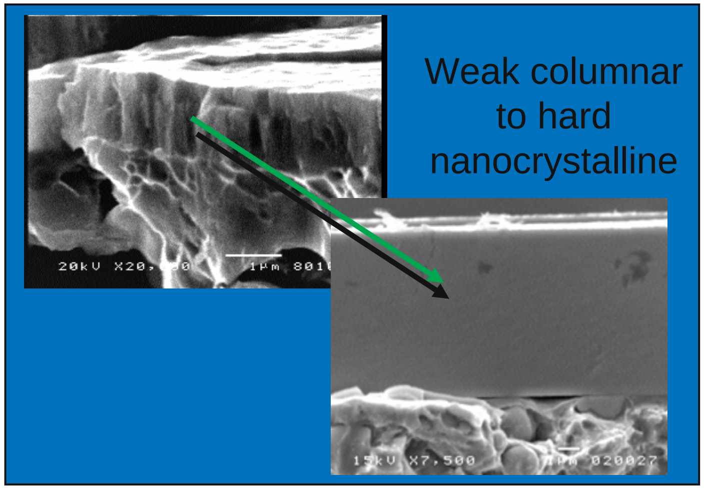
Coated H13 Steel Disk

Pin-on-Disc Evaluation of Low-Friction Superhard Coatings – 50 % Reduction in Boundary Layer Friction





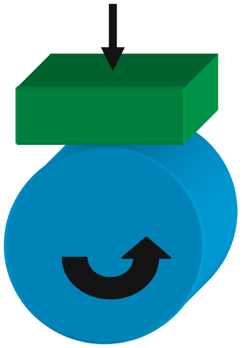
- Engineered coating microstructure and composition to provide superhardness and tribochemistry for enhanced low-friction properties



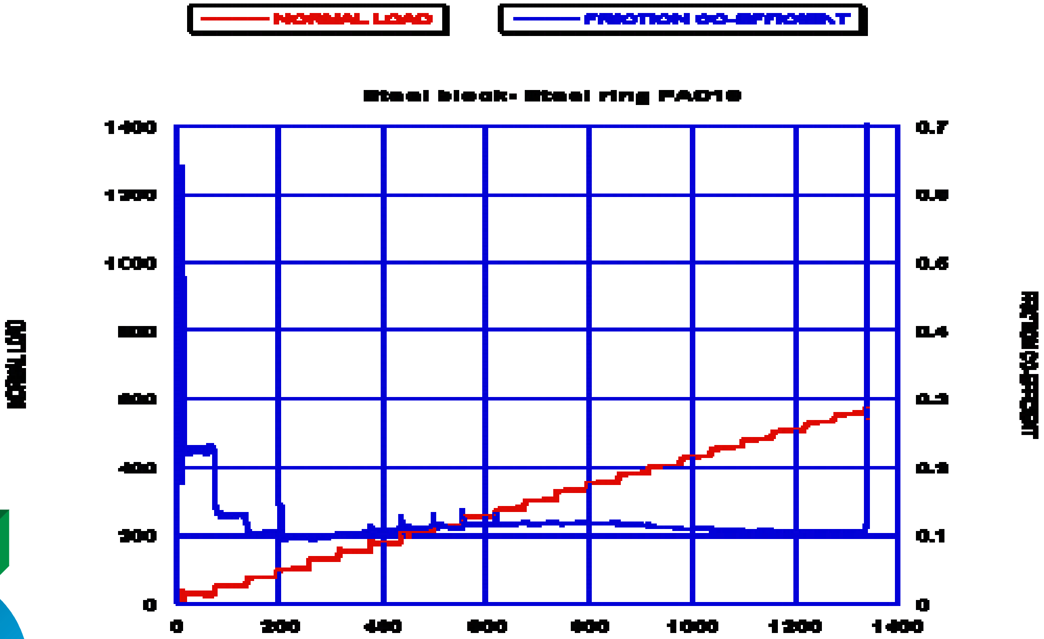
Weak columnar to hard nanocrystalline

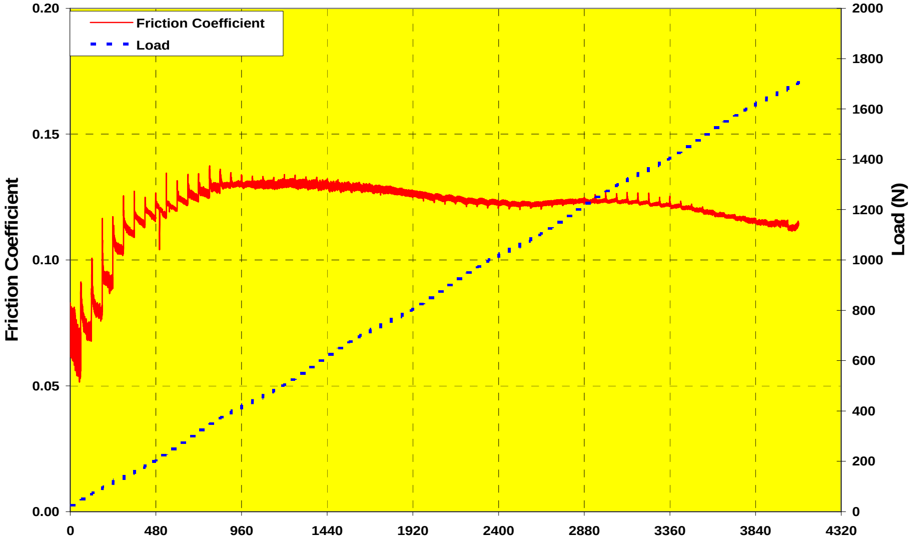
Block-on-Ring Evaluation of Scuff Resistant Coatings

Steel/Steel
600 N
scuffing
load

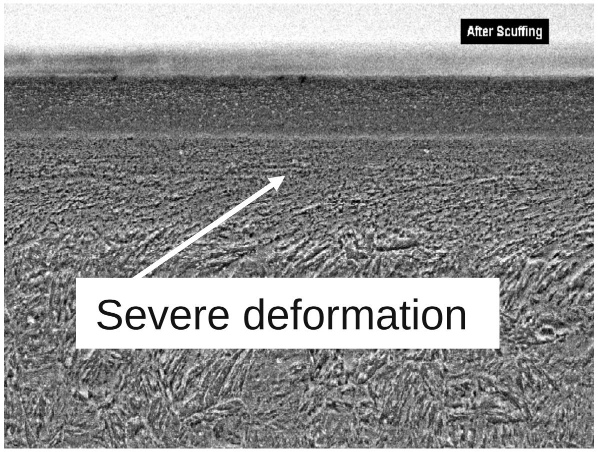


SHNC/SHNC
>1700 N
scuffing load



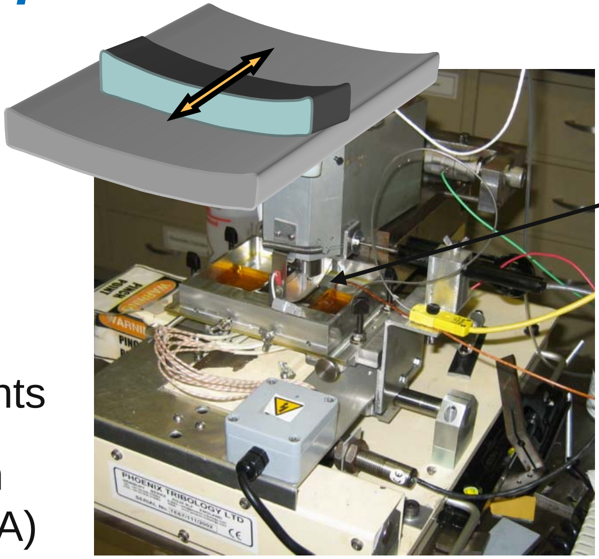


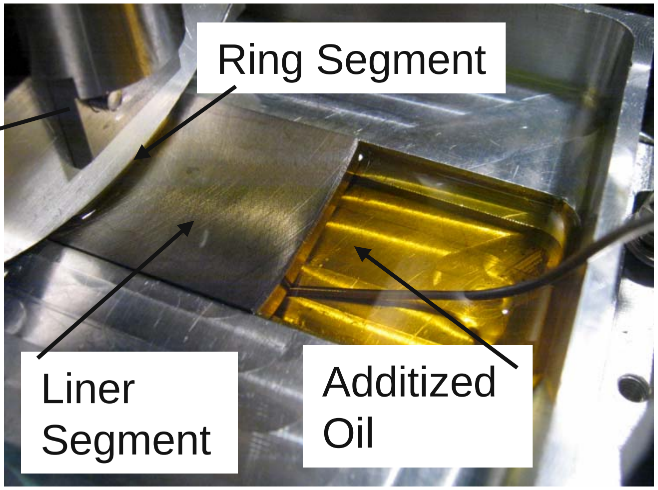
- Low-friction technologies must also maintain or improve the durability and reliability of critical engine components – a challenge for low-viscosity lubricants.
- Strategies are being developed to identify pathways to improve scuff-resistance while enabling use of low-friction, low-viscosity lubricants

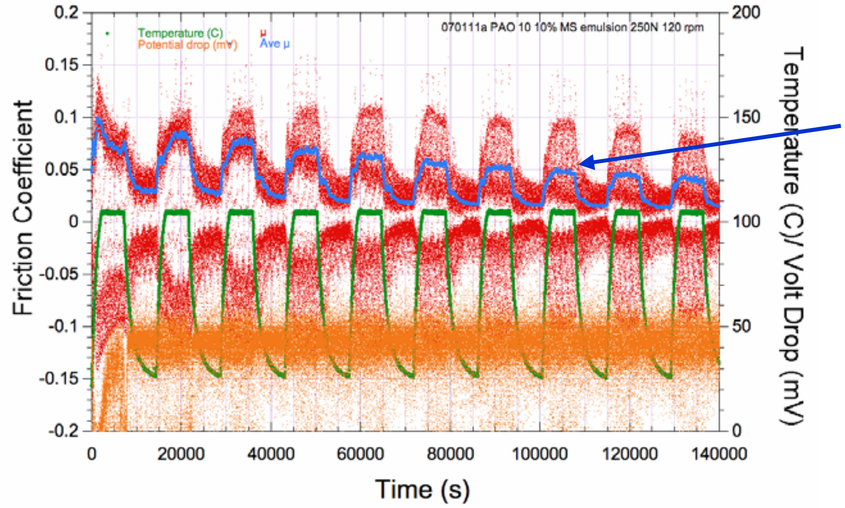


Technology Development & Validation – Low-Friction Additives

- **Development of Low-Friction Additives**
  - Developed test rig to simulate ring-on-liner and piston-on-liner tribological environments
  - Discovered low-friction nature of boric-acid (BA) based additives, Developed concept of boric-acid based additives (fuels & lubes)
  - Developing technology to produce nm-sized BA additives
  - Demonstrating low-friction properties of BA in lab tests prior to engine validation studies





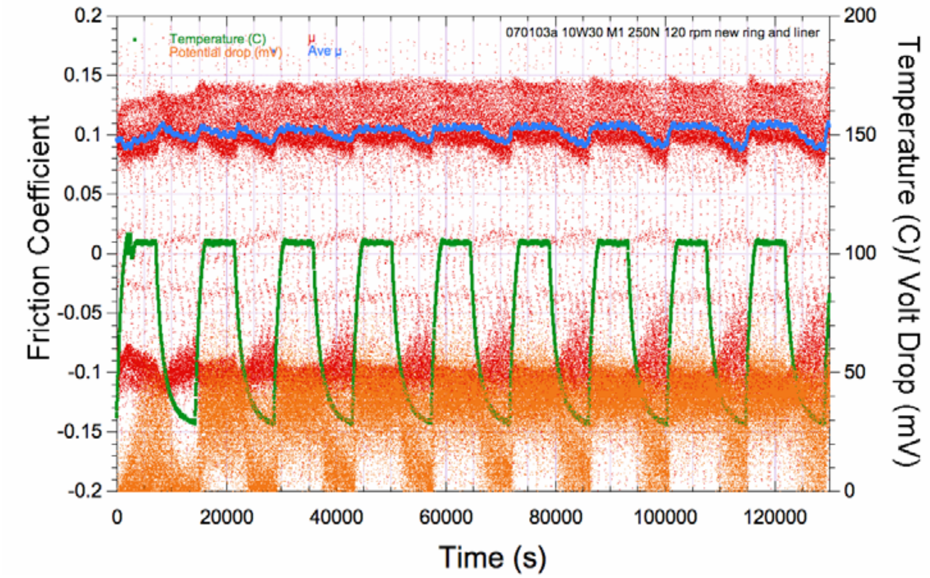


Blue trace shows friction coefficient during cyclic heating tests – Note how cyclic heating activates the action of the BA additive to produce low friction

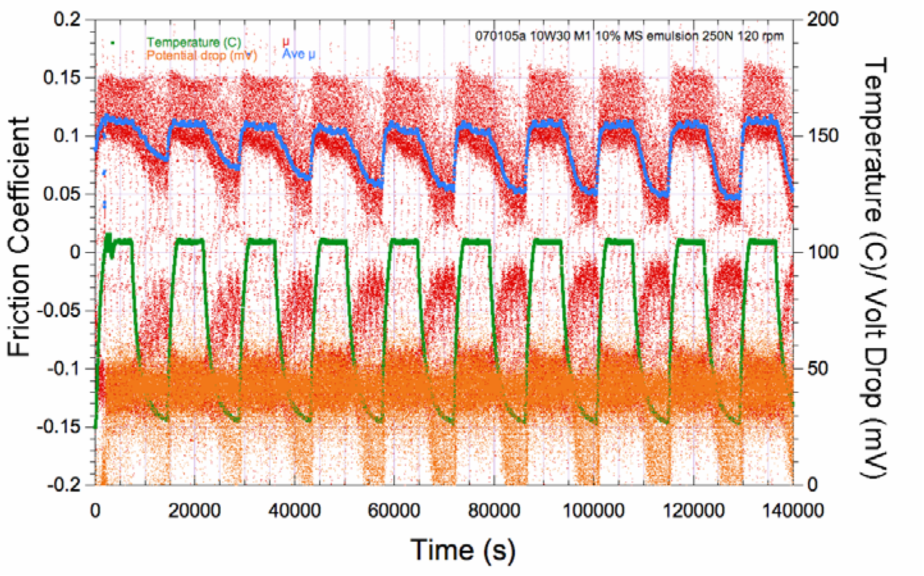
10W30 synthetic + 10 % E Additive

- Comparison:
  - No significant difference in contact resistance in time or between different lubricants
  - It can be shown that the decreases in friction at low temperature as cycles occur are due to greater hydrodynamic lubrication as a result of fine polishing of the liner

10W30



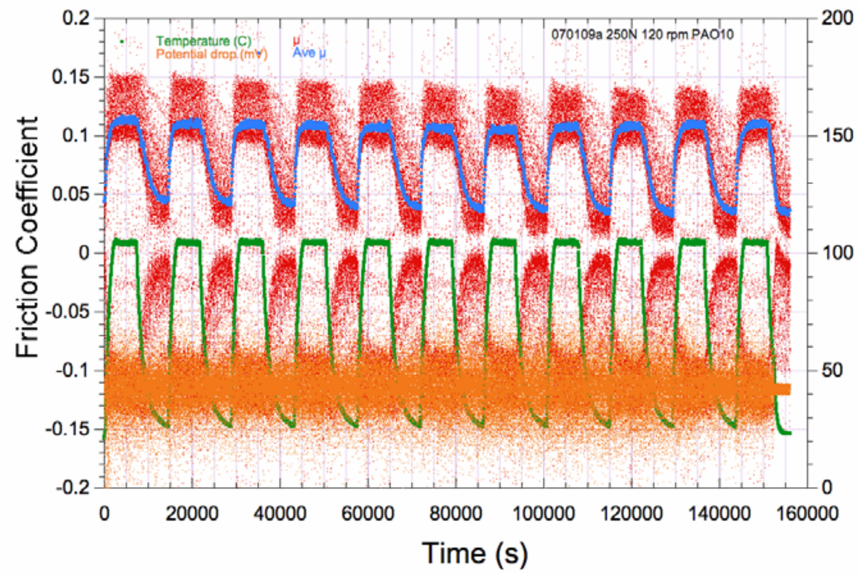
10W30 + E Additive



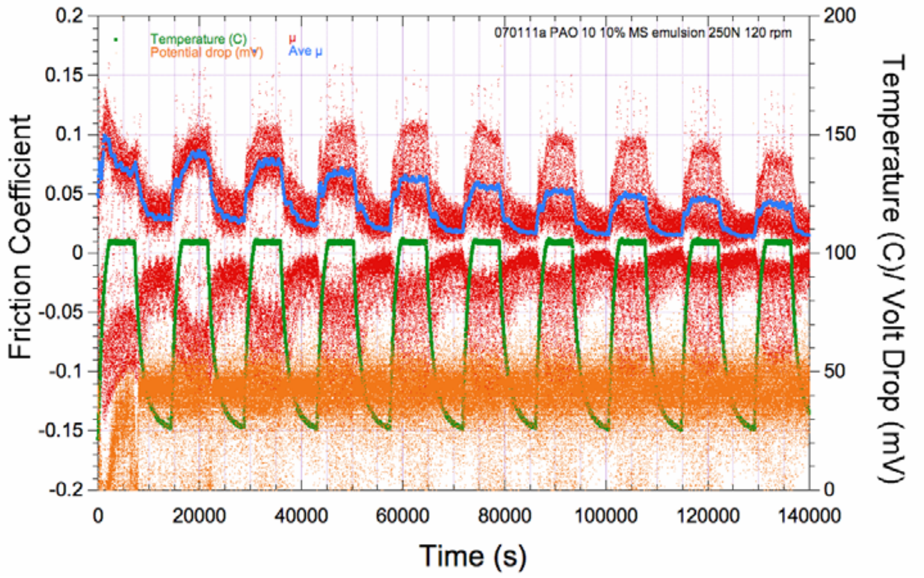
PAO 10 + 10% E - Additive

- Specimen and cup were cleaned well to remove any chemical additives and filled with PAO 10
  - Boundary friction at 100°C = 0.108
  - Minor change of friction at low temperatures as tests progress
  - Significant Impact of E Additive on friction

PAO 10

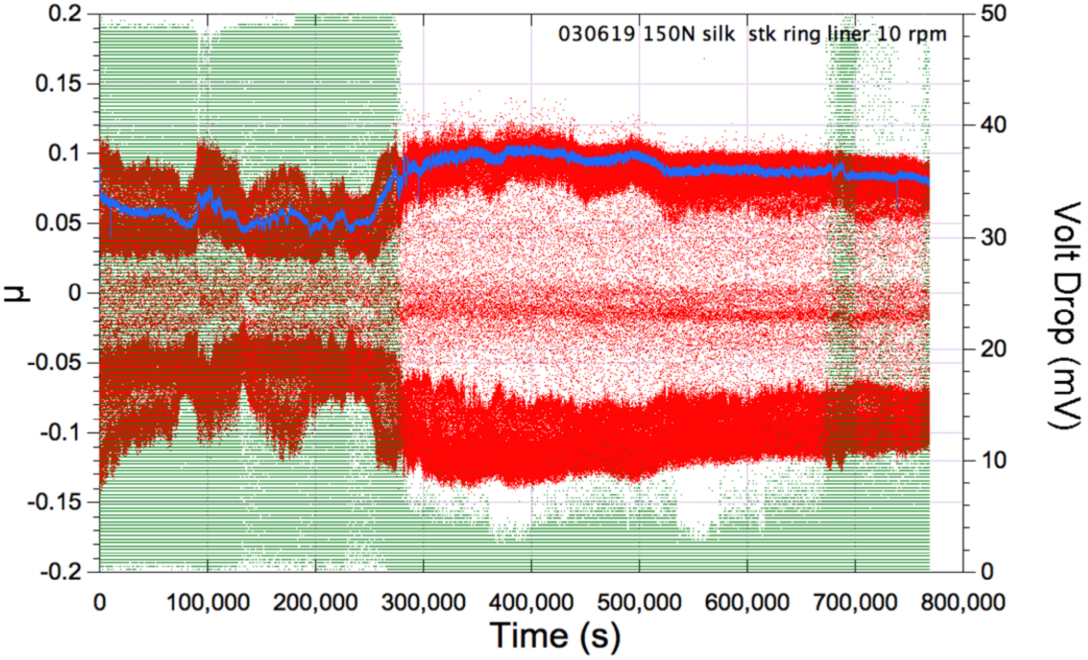


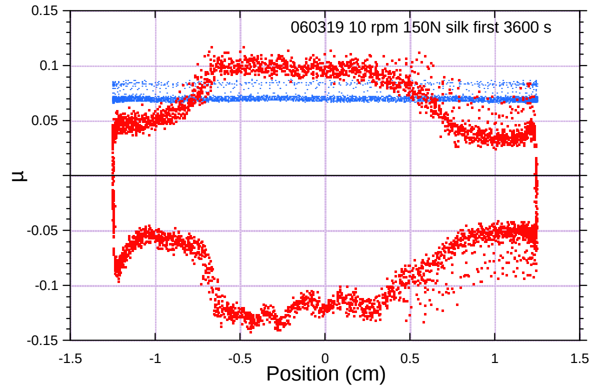
PAO 10 + E - Additive

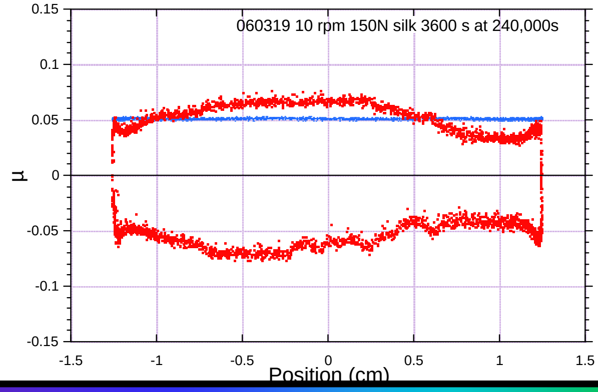


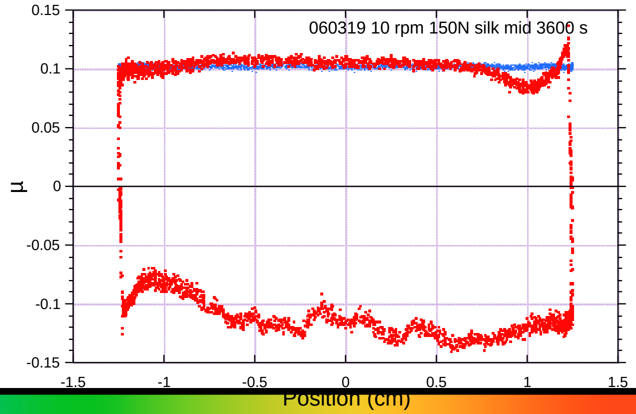
Low-Friction Additive Consumed During 9-Day Benchtop Test

- During extended break-in tests with low-friction additive, the friction was initially low, continued to decrease, then increased as the additive was depleted



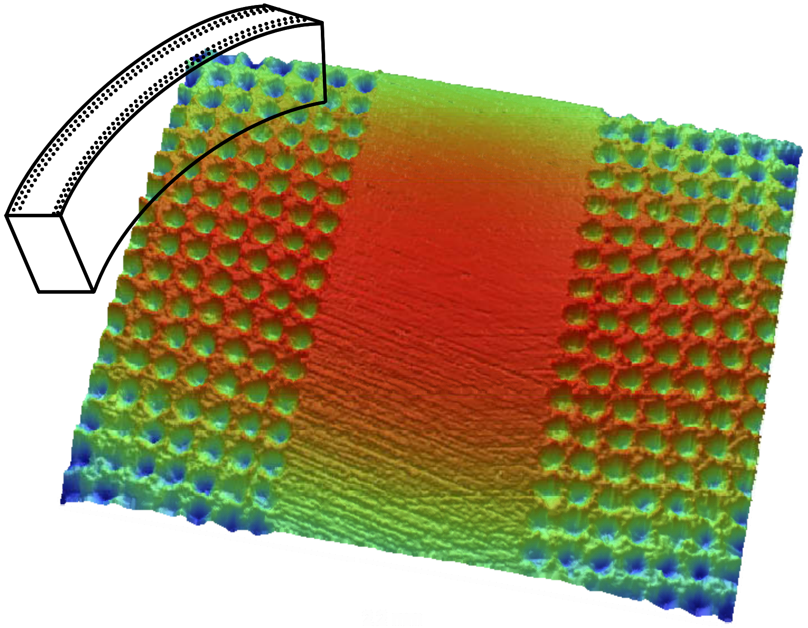




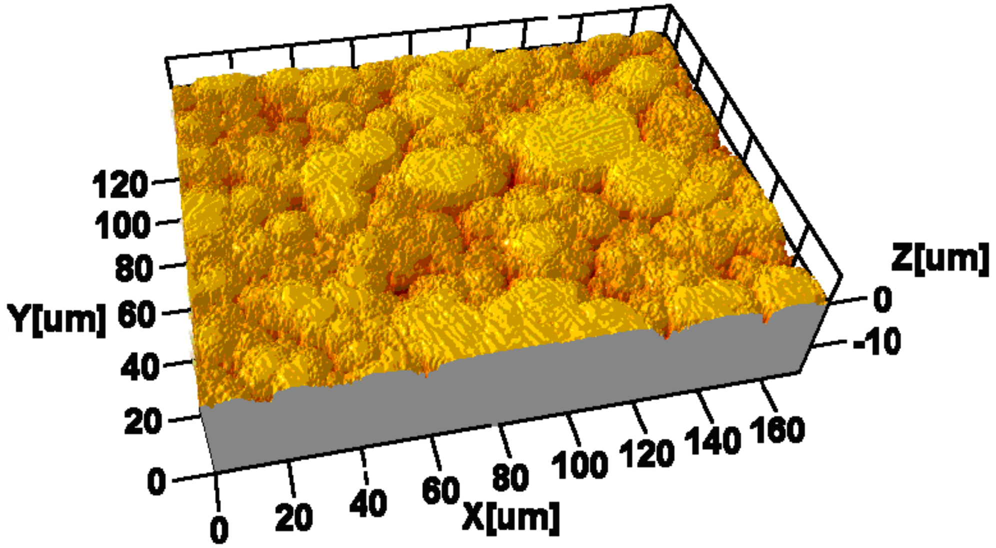


Textured Surfaces

- Textured surfaces with ‘oil reservoirs’ produced by laser dimpling or control of coating morphology during deposition

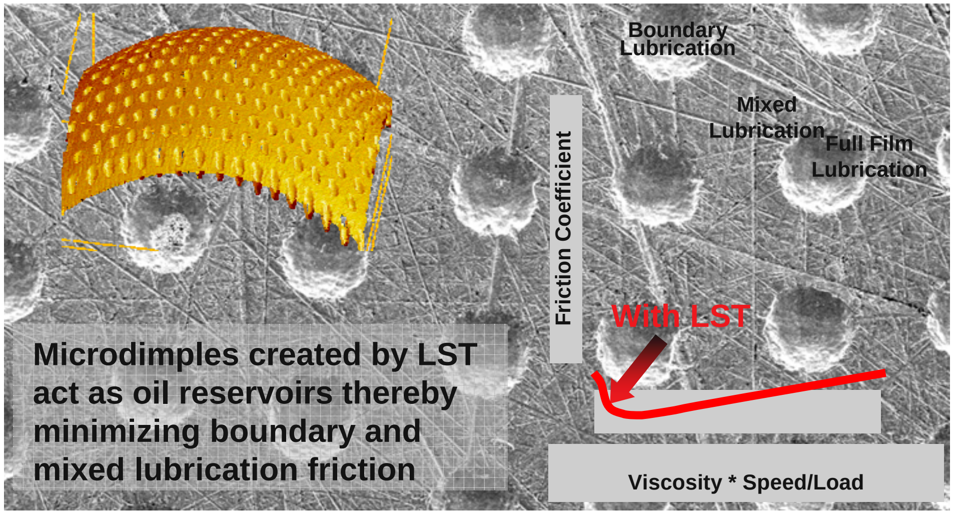


Partial Laser Texturing of Hard Cr Coated Cylindrical Piston Ring – Etsion (COST June 2007)



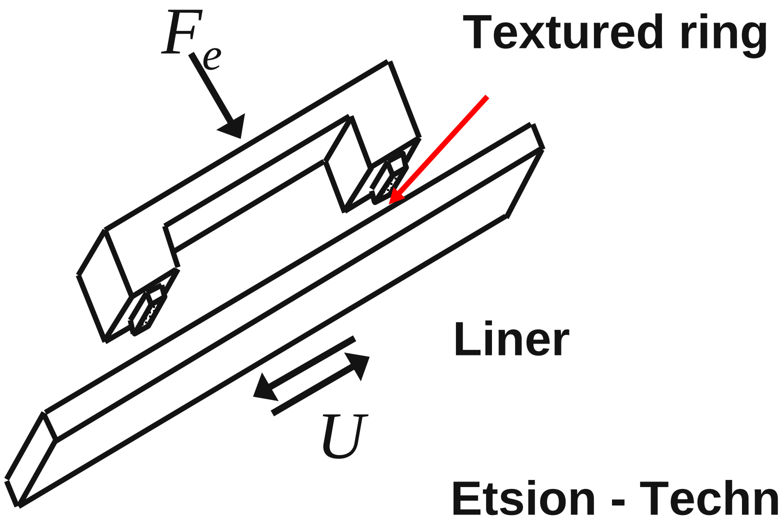
Hard (1800 H_K), Electroless Ni_3B Coating After ‘Plateau Polishing’ – UCT Defense, LLC

Textured Surfaces as a Method to Reduce Hydrodynamic and Mixed Lubrication Friction

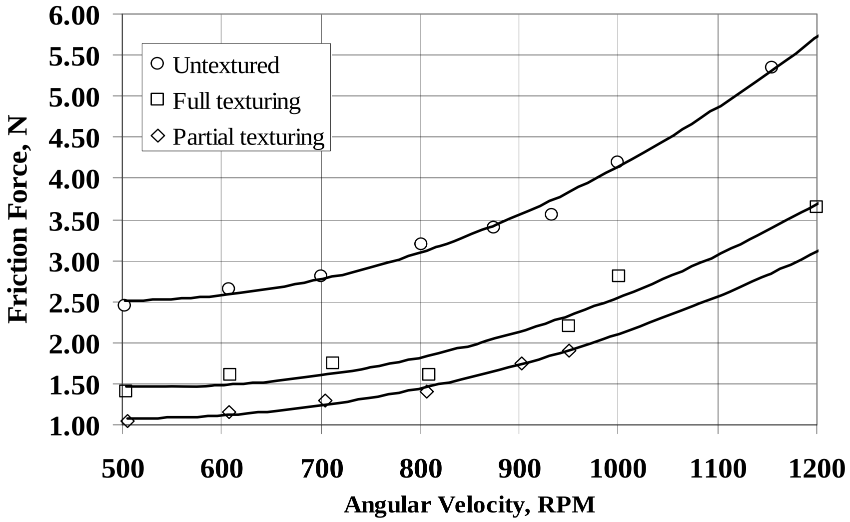


Microdimples created by LST act as oil reservoirs thereby minimizing boundary and mixed lubrication friction

- Argonne (in collaboration with Technion University – Prof. I. Etsion) is evaluating the potential of laser surface texturing to reduce friction on engineered surfaces
- Results suggest LST may provide significant energy savings regimes where **conformal contact** is present

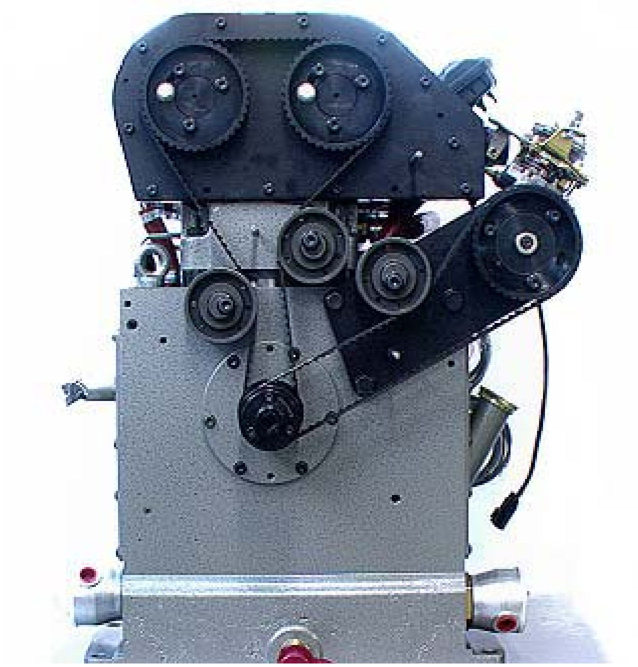


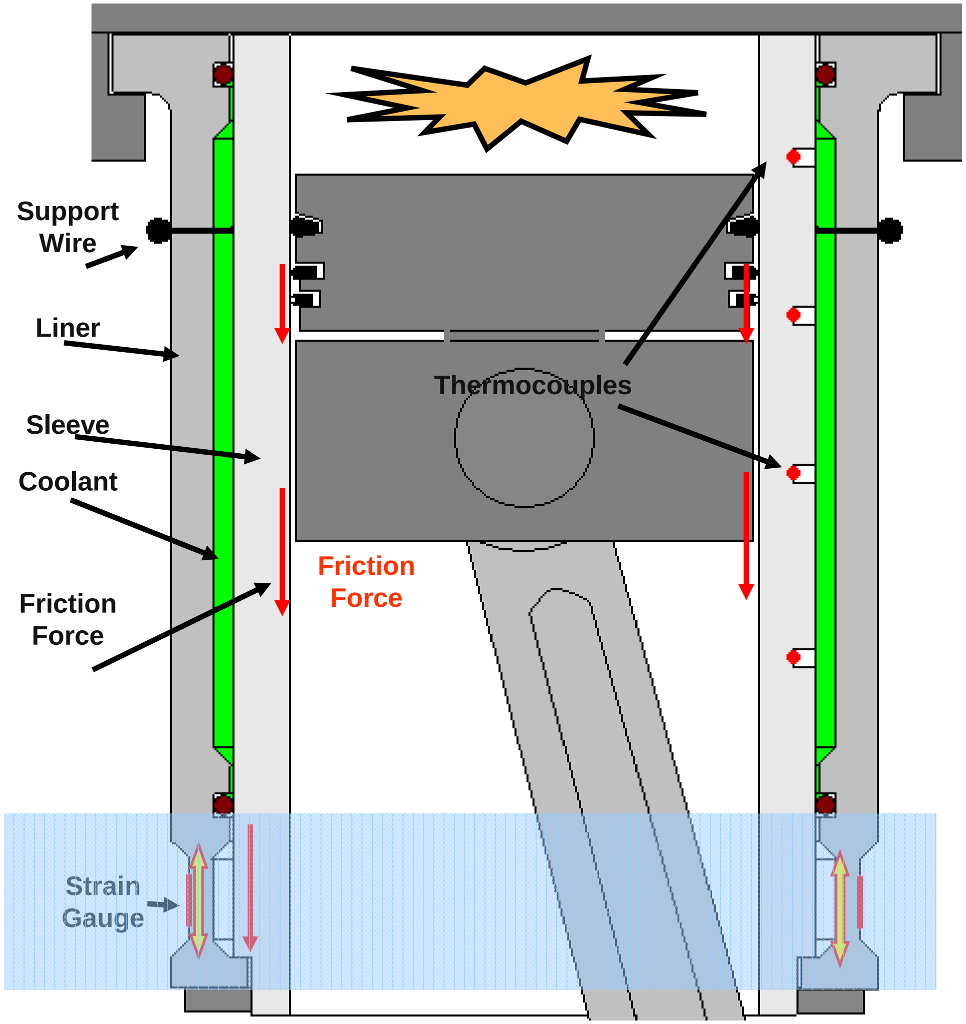
Etsion - Technion



Ricardo/U-Mich – In-Cylinder Validation of Models and Low-Friction Technology

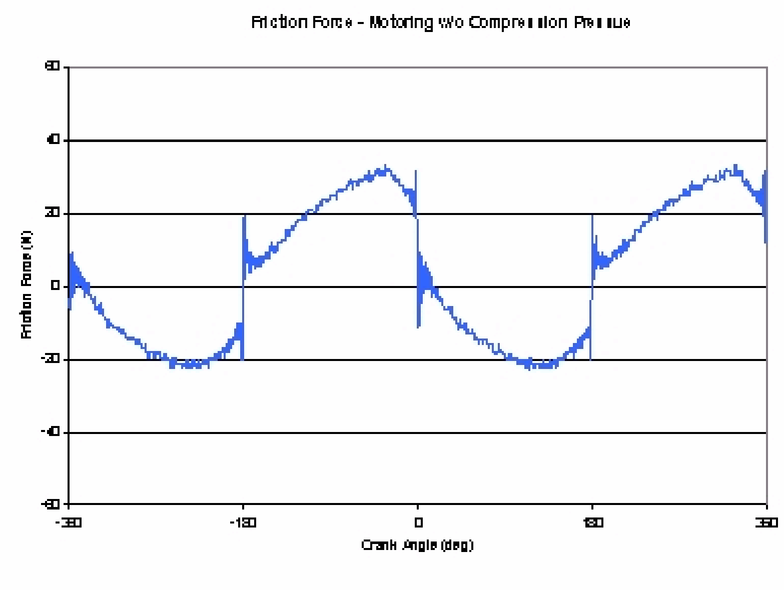
- Single Cylinder, Fired Diesel Test Engine – Ricardo Hydra
- Engine Modified to Monitor Friction Force Between the Piston (Skirt & Rings) and Liner Continuously

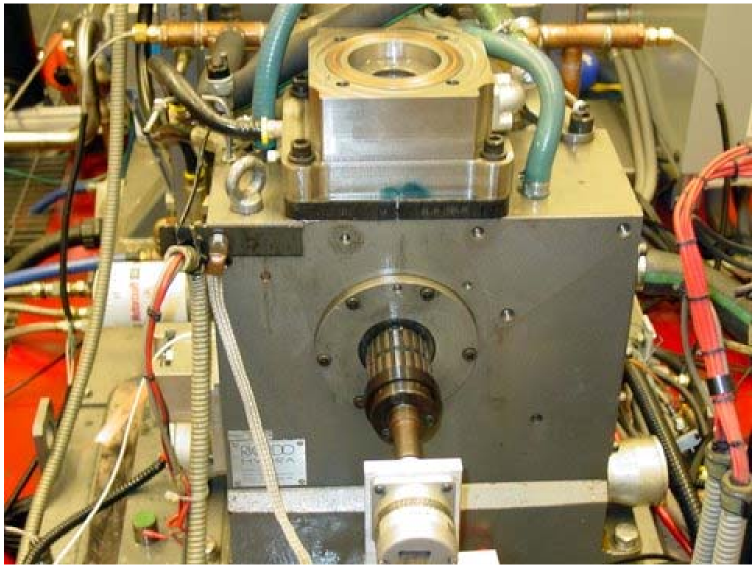




In-Situ Measurement of Ring/Piston – Liner Friction

- U-Michigan instrumented liner installed in single-cylinder Hydra engine
- Preliminary friction force trace as a function of crank angle under motored conditions
- 4-valve DI cylinder head to be installed for in-situ friction force measurements under fired conditions





Summary & Future Directions

- Significant Fuel Savings can be Achieved by Reducing Parasitic Friction Losses in Engines and Drivelines
  - 3-5% - Engine
  - 2-4% - Driveline
- Suite of Mechanistic Models Integrated to Examine the Role of Low-Friction Technologies and Low-Viscosity Lubricants on Fuel Savings
- Benchtop/Lab Techniques Identify Potential Pathways to Low-Friction Technologies
  - Depending on operating conditions, boundary friction reductions up to 90 % can be achieved
- Engine Validation Studies in-progress

- Future Directions
  - Single-cylinder studies
  - Low-friction technology development & evaluations
  - Multi-cylinder validation
  - Accessories – modeling of parasitic friction losses

Acknowledgement

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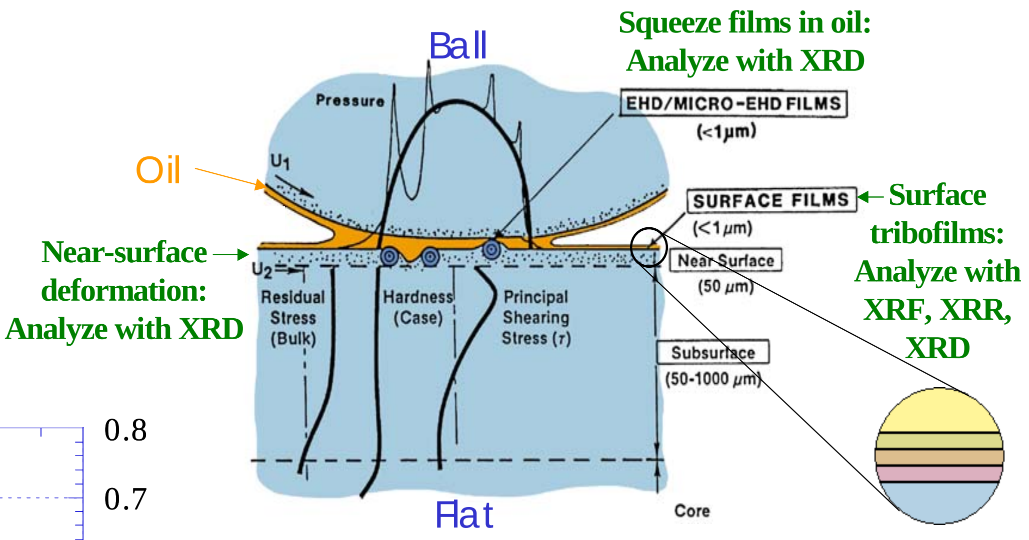
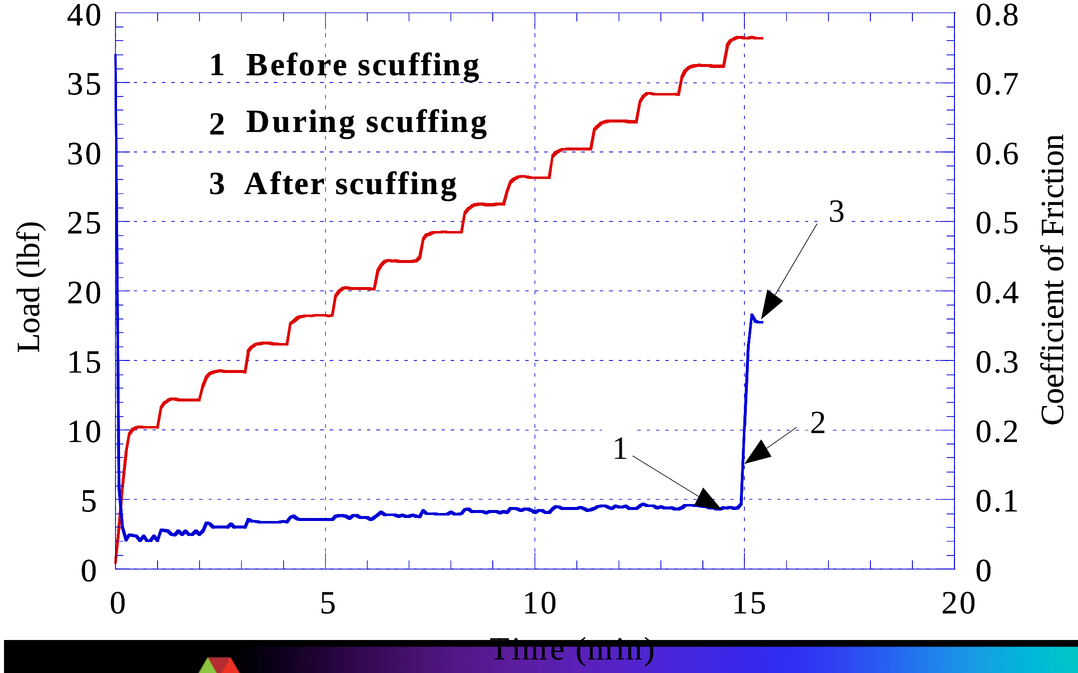
Boundary Lubrication Mechanisms – Scientific Understanding of Friction, Wear, & Lubrication

- Developing and using advanced x-ray techniques to investigate friction and wear mechanisms
  - Formation of protective tribofilms
  - Surface failure mechanisms (Scuffing)

Using the APS to analyze boundary lubrication





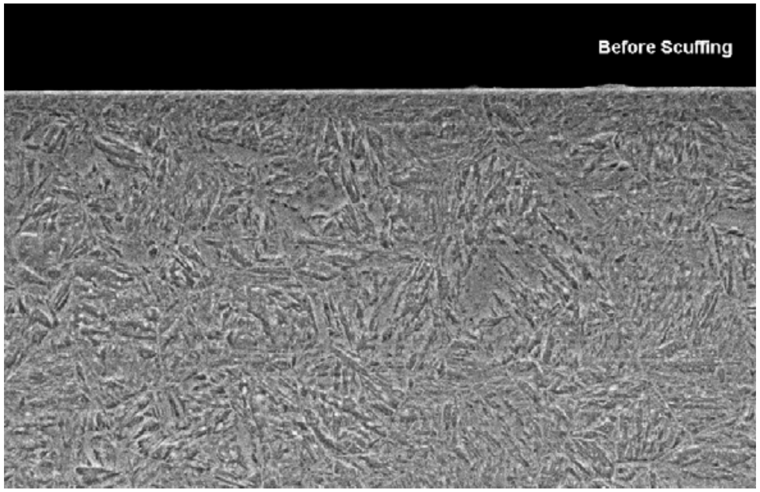
ANL model predicts that the critical shear strain to initiate scuffing is given by:

$$\gamma = \frac{npC_v}{0.9\frac{\partial\tau}{\partial T}}$$

Progression to Scuffing

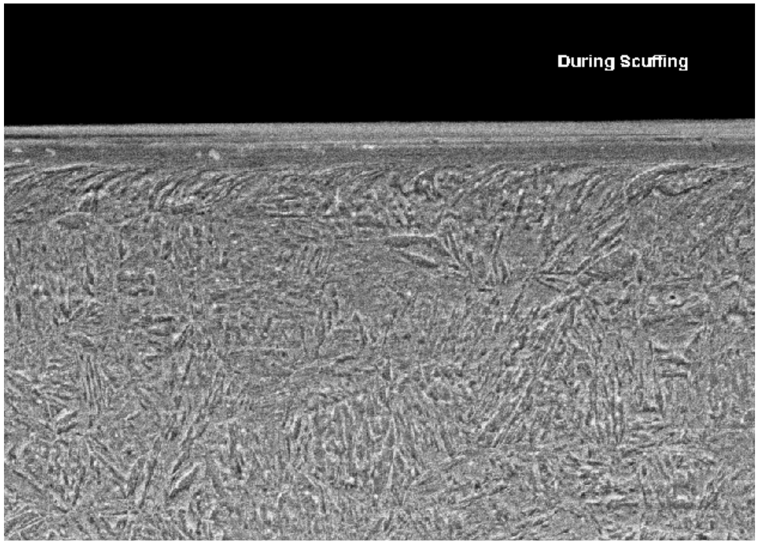
Scuffing produced severely deformed surface layer (~ 20 µm) in fraction of second.

1



20 µm

2



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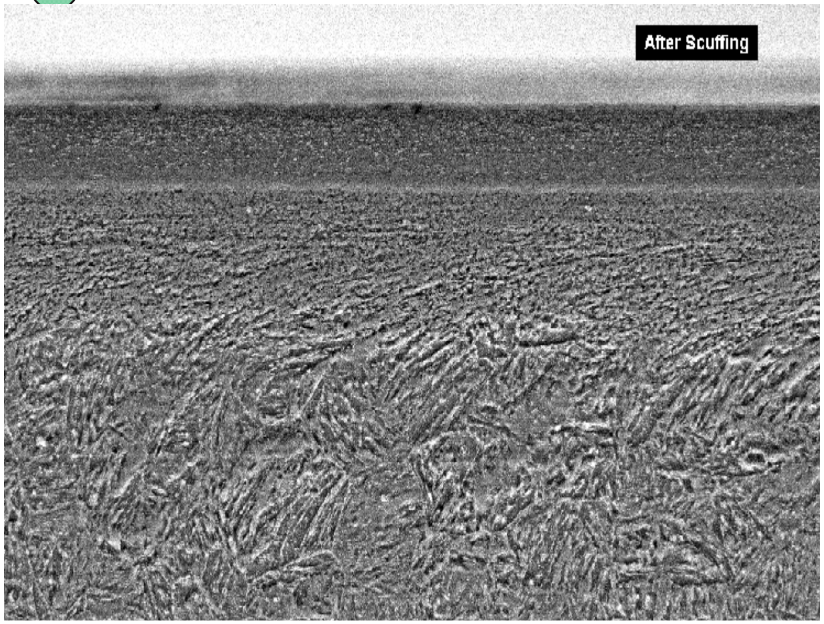

10W30 synthetic + 10 % E BA

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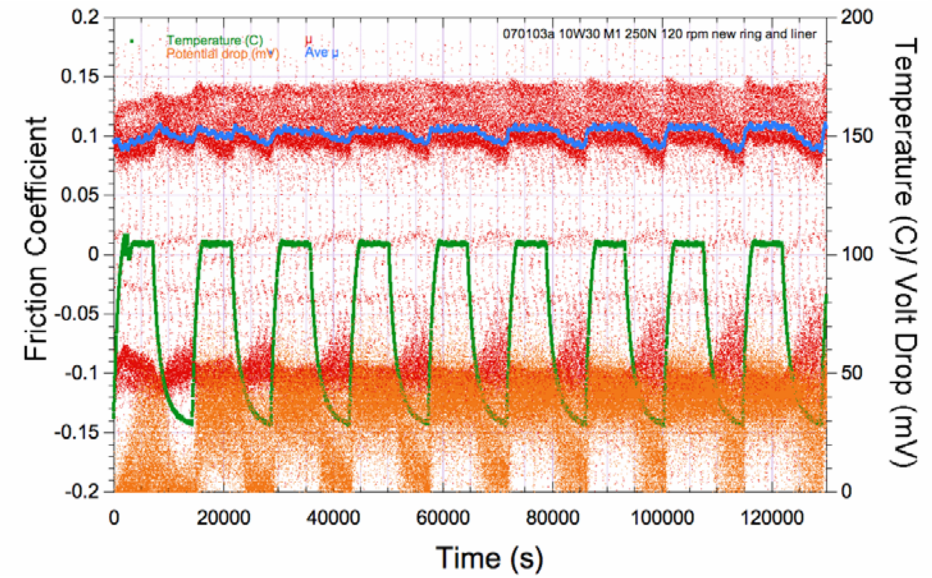
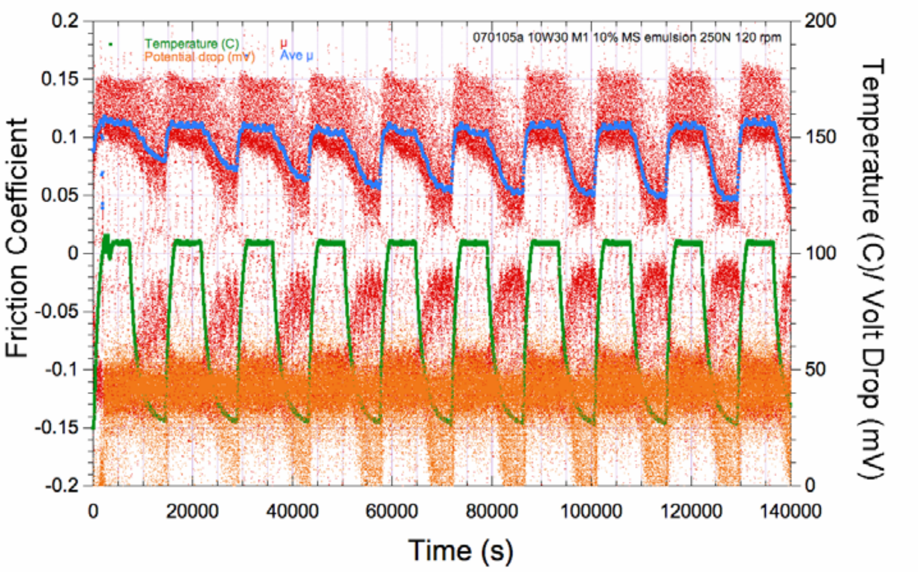
10W30

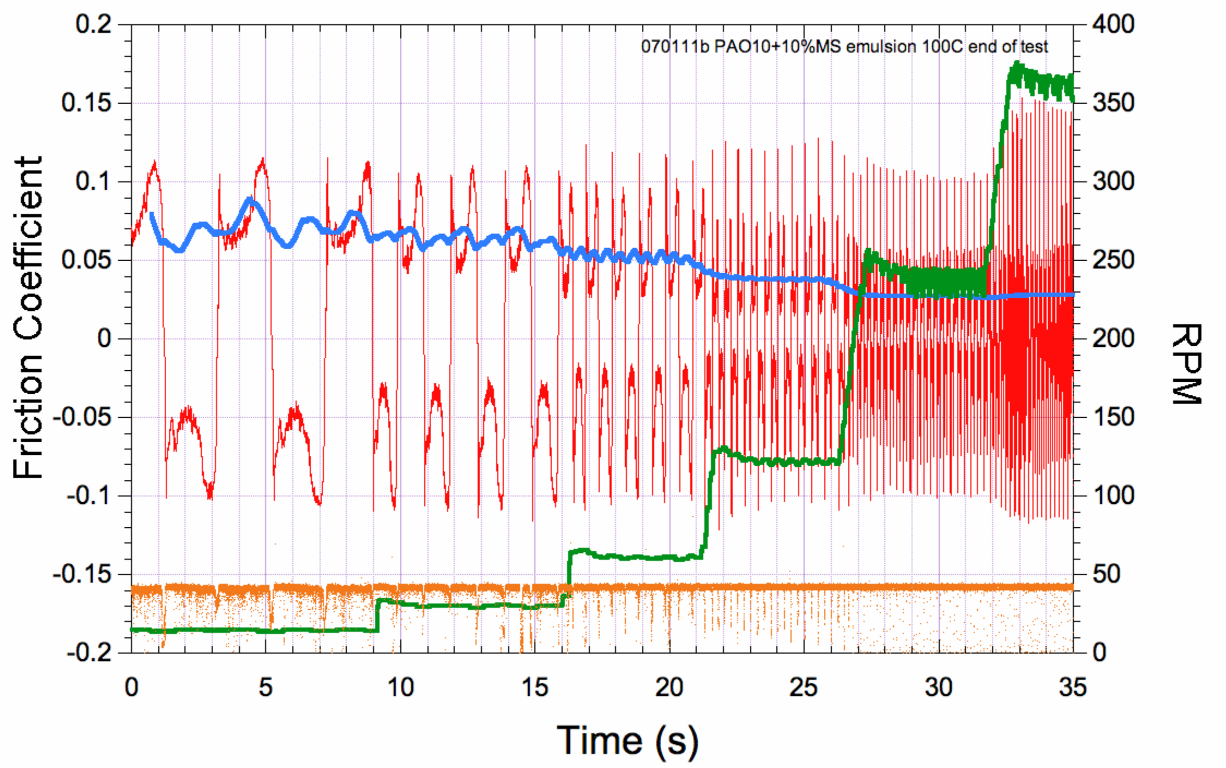


10W30 + E BA



Transient Speed Tests - PAO 10 + 10% E - Additive

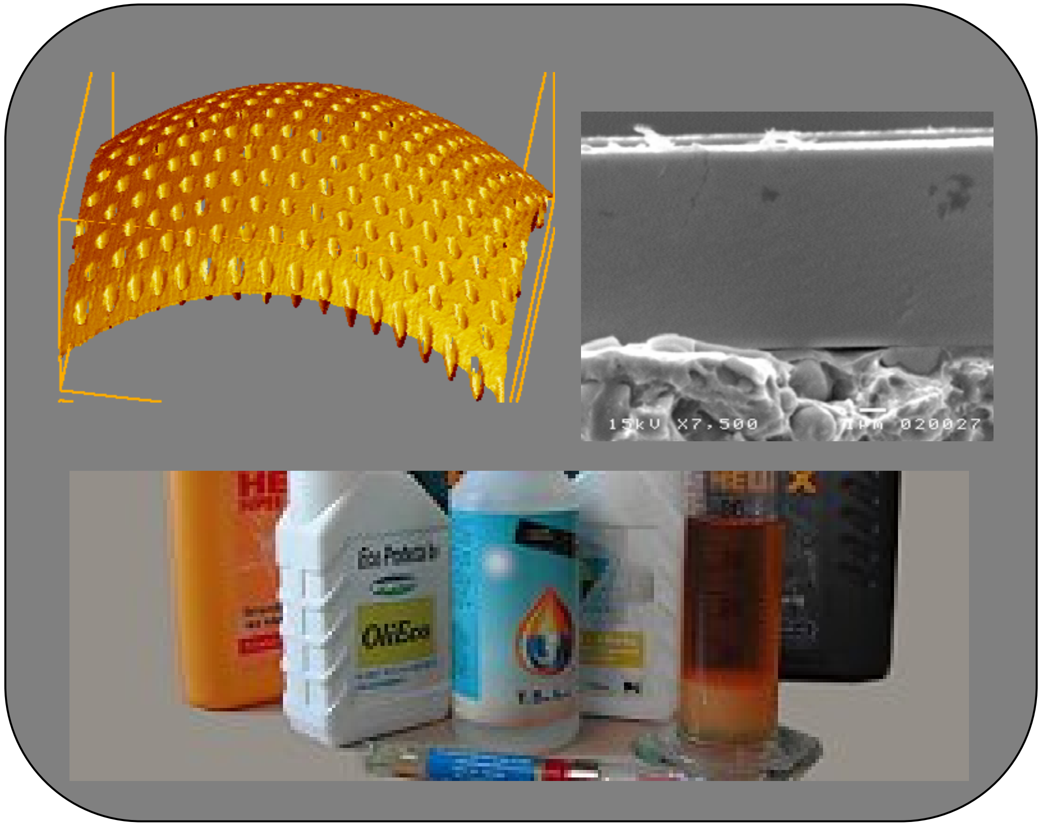
- Data were obtained at 100 C at end of test for various reciprocating speeds:



Benchtop Studies – What Is the Magnitude of Friction Savings That Can be Achieved, and What Level of Increased Protection

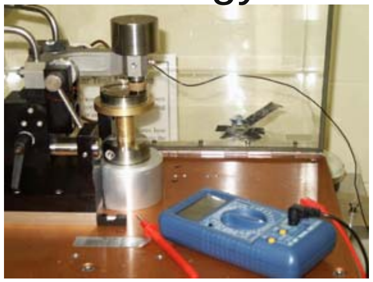
- **Models assumed 30, 60, and 90% reductions in boundary friction – what are realistic friction coefficients, how do they compare to the baseline assumptions – are there technologies that can provide these levels of improvements**

- **Pin-on-Disc, Reciprocating, Block-on-Ring, and Ring-on-Liner Configurations**
  - Friction, Wear, Scuffing-Resistance of test coupons and prototypic rings and liner segments
- **Coatings, Surface Texturing, and Additives**



Technology Development to Technology Implementation & Commercialization

- Argonne's Tribology Section heavily focused on technology development, evaluation, and testing.
- Develop close alliances with industry to validate prototype components and commercialize technology



Technology Development

Coatings

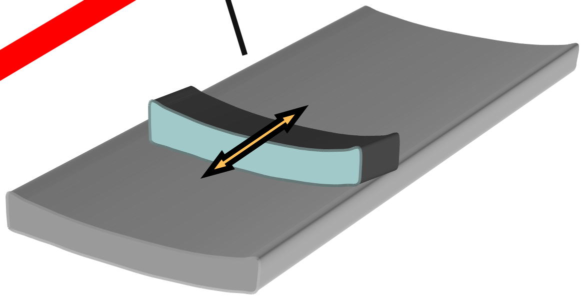
Lubricants

Nanofluids, etc.

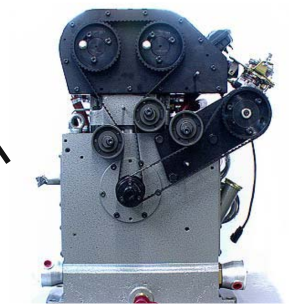
Benchtop Tests

Component Rig Tests

Ring & Liner



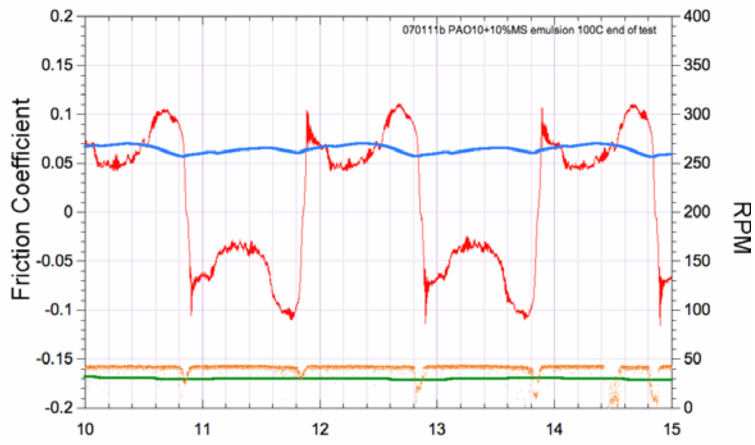
Fired Single Cylinder Engine Validation

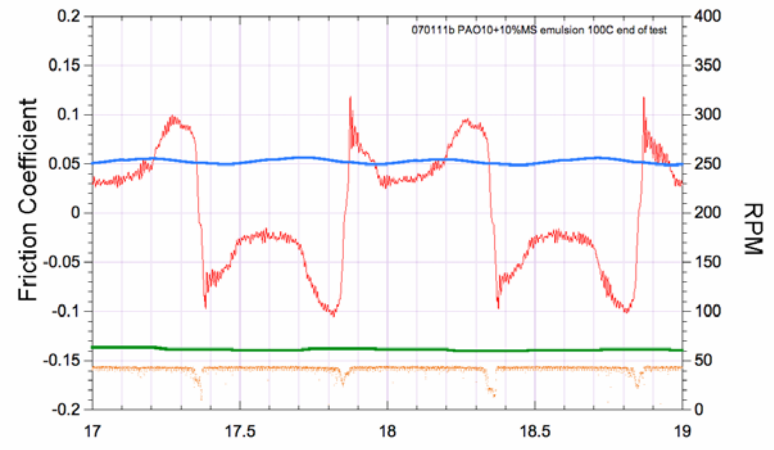


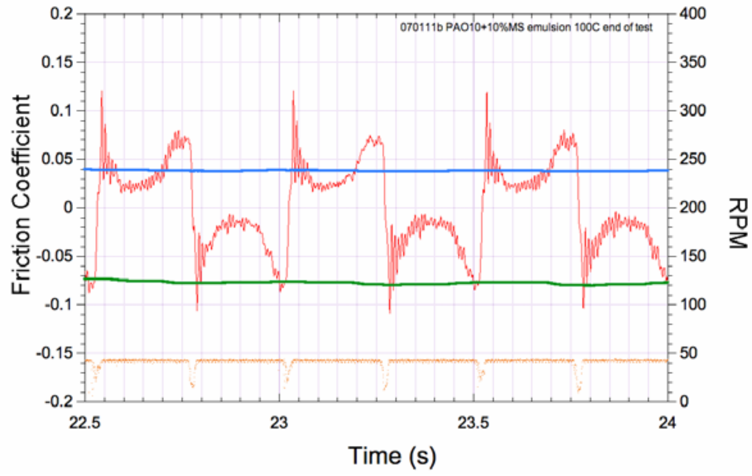
MultiCylinder Engine/Transmission Validation

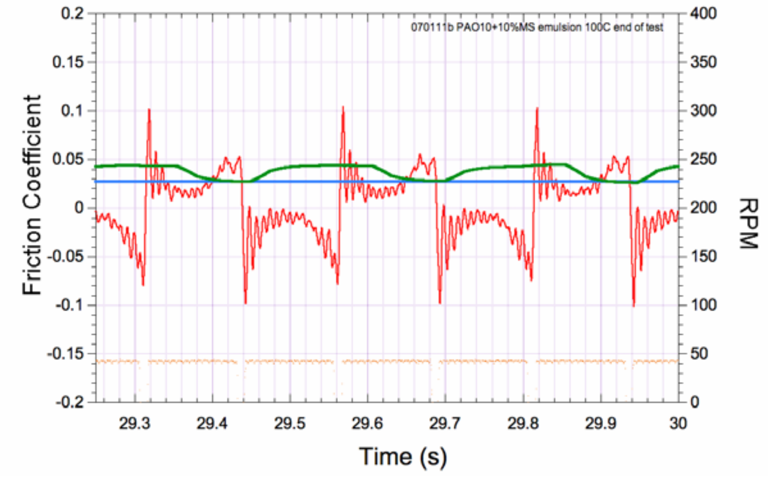
Ramped Speed Tests - PAO 10 + 10% E - Additive

- Sliding is strongly hydrodynamic, even at *slowest* sliding speeds
  - Thus, actual boundary friction coefficient cannot be determined from these graphs









Friction Analysis - PAO 10 + 10% E - Additve

- Graphs of friction at 100°C as a function of position near start of test and near end of test are strikingly different from each other
- Near end of test, sliding is largely hydrodynamic, even at 100°C