Low-Friction Engineered Surfaces

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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

15% of IMEP
(Indicated Mean Effective Pressure – HP normalized to engine displacement)
**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
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

\[ \text{FCSF} = \frac{\text{IMEP} + \Delta \text{FMEP}}{\text{IMEP}} \]

(Fuel Consumption Scaling Factor)

- 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

* interface considered in current study
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**

![Graph showing the relationship between piston FMEP and viscosity grade.]

**Normalized Piston - Liner Contact Severity**

![Graph showing normalized piston-liner contact severity.]

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**Argonne National Laboratory**
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

![Graph showing the impact of reduced asperity friction on fuel savings.](chart.png)
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
  - $10^6$ lower

Test Conditions:
- Load: 10 N
- Speed: 0.5 m/s
- Distance: 1305 km
- Environment: Dry N₂
- Temperature: 22°C
- Wear rate: $7.4 \times 10^{-11}$ mm$^3$/N.m
- Coated M50 Steel Ball (9.5 mm diameter)
- Coated H13 Steel Disk

17,500,000 passes

Test machine failed
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

15W-40 Formulated Mineral Oil

Friction Coefficient vs Sliding Distance (cm)

- Weak columnar to hard nanocrystalline
Block-on-Ring Evaluation of Scuff Resistant Coatings

- 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.

Steel/Steel
600 N scuffing load

SHNC/SHNC
>1700 N scuffing load

Severe deformation
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**

- 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.
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
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

- 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.
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
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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

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

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

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

Scuffing produced severely deformed surface layer (~ 20 µm) in fraction of second.
10W30 synthetic + 10 % E BA

- 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 liner wear during running
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.
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 - Additive

- 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.