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Overview of Friction and Wear Reduction for Heavy Vehicles

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Overview

Timeline

- Project start date FY 06
- Project end date FY 13
- Percent complete 33%

Budget

- Total Project Funding ~4.3M
  - DOE Share* ~4M
  - Contractor Share* ~0.3M
- FY 08* ~1M
- FY 09* 1.1M

* Supports 4 projects, Costs do not include cost share from propulsion material projects

Barriers

- Barriers addressed - FCVT/VT Heavy Vehicle Systems Barriers (3.1.2.8)
  - Safety, Durability, Reliability
  - Computational models, design and simulation methodologies
  - Higher vehicular operational demands

Partners

- Ricardo & University of Michigan
- Eaton, Caterpillar, & NU
- Mahle
- CemeCon & Hauzers
- TARDEC

Objective/Relevance - Develop models, technologies, and tools necessary to reduce parasitic friction losses (efficiency) and improve wear (reliability/durability) of engine and driveline components

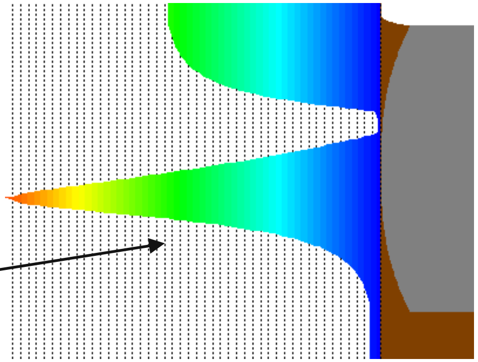
- **Fuel efficiency**
  - 10 to 15% of fuel consumed is lost to friction (more than is delivered to the wheels). Research on boundary friction and low viscosity lubricants show potential to reduce fuel consumption 4-5 %
- **Reliability/durability**
  - Low-friction, low-viscosity fluids will require advanced materials, coatings, and additive formulations to maintain and/or improve engine durability and reliability.
  - Advanced, compact, high-performance powertrains will require advanced materials and coatings to mitigate high contact loads
- **Emissions compliance**
  - Implementation of diesel emission-control devices require low-P, low ash additive packages that mitigate catalyst degradation
  - Introduction of EGR will accelerate degradation of lubricants - requiring EGR-tolerant lubricants
- **Alternative fuels**
  - Impact of fuel dilution of lubricant performance unknown for bio-derived fuels

Objective of Friction and Wear Reduction Projects

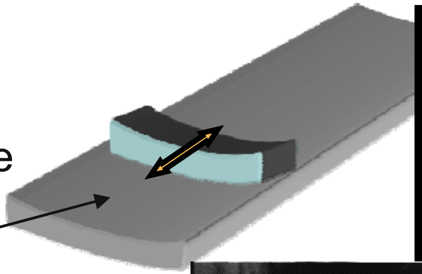
- This cluster of projects addresses the development of the science and technologies needed to reduce friction and wear in advanced heavy vehicles (engines and drivetrains)
  - **Boundary Layer Lubrication (FWP 43387; Agreement # 8979)**
    - *investigation of friction and wear mechanisms under boundary and mixed lubrication regimes, and development of wear models* ***(poster - VSSP01)***
  - **Parasitic Energy Loss (FWP 49371; Agreement # 8671)**
    - *development and application of mechanistic models to predict impact of friction and lubricant viscosity on fuel economy, application of lab-tests to identify candidate low-friction technologies, and validation of models* ***(oral presentation - VSS17)***
  - **Low-Friction, Hard Coatings (FWP 49370 & 49558; Agreement #s 13648 & 13721; co-funded by VT01-01 & VT05-04)**
    - *development of low-friction, low-wear coatings, materials, and additives* ***(poster - VSSP04)***
  - **Residual Stress Measurement in Thin Films (FWP 49435 & 49362; agreement #s 13648 & 13723; co-funded by VT 01-01 & VT 05-04)**
    - *development of advanced x-ray analytical techniques to measure residual stresses in advanced tribological coatings, and optimize coating adhesion* ***(poster - PMP17)***

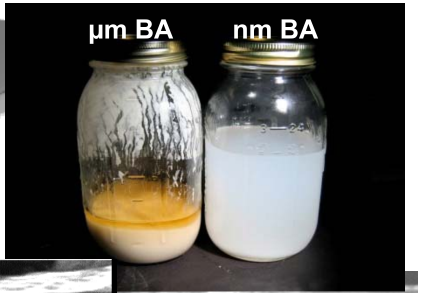
Approach

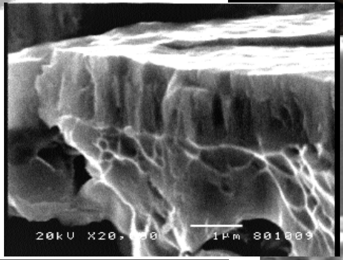
- **Develop and Apply Mechanistic Models** of Friction (Boundary and Viscous) Losses to Predict Parasitic Losses as a Function of **Engine Conditions** (Load & Speed), and **Tribological Conditions** (Boundary Friction and Oil Viscosity)
- **Evaluate/Screen the Potential of Candidate Surface Treatments and Additives** to Reduce Boundary Friction Under Lab Conditions Prototypical of Engine Environments
- **Develop Advanced Surface Treatments and Additives** that Provide Low Friction and are Robust, Reliable, and Durable
- **Develop Tools and Theories** to Understand and Model Complex Physical Phenomena in Tribological Environments
- V**alidate Codes/Models and High-Potential Solutions** in Fired Engines Using In-Situ Friction Measurement Techniques
- **Demonstrate efficiency improvements** in multi-cylinder engines

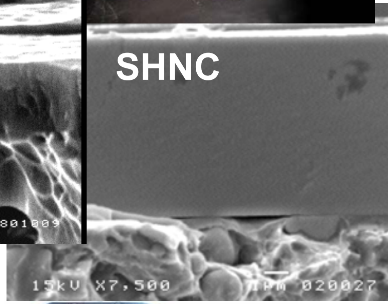


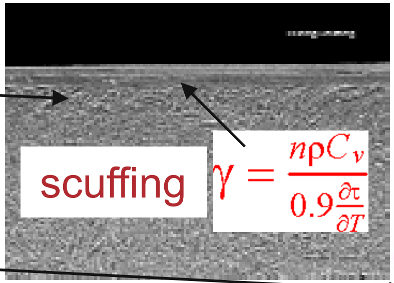
RINGPAK
PISDYN
ORBIT
VALDYN



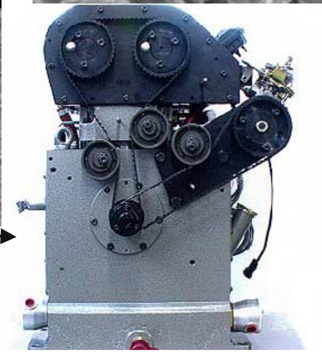








$$\gamma = \frac{n\rho C_v}{0.9\frac{\partial\tau}{\partial T}}$$



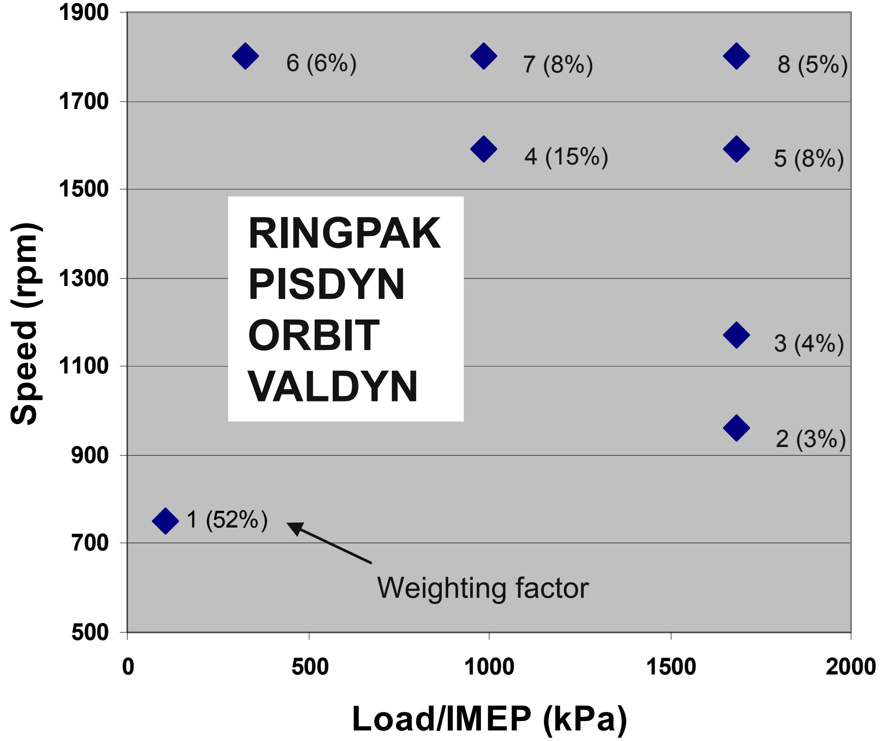
Milestones

- FY 2008 (completed)
  - Integrated engine model on the impact of friction on efficiency
  - Development of test protocols to simulate friction between piston skirt and liner
  - Development and evaluation of superhard, low-friction coating
  - Demonstration of FIB (focused ion beam microscopy) tool to characterize tribo-films
  - Demonstration of x-ray tool to measure residual stresses in thin films

- FY 2009 (on schedule)
  - Evaluation of low-friction skirt coatings and additive packages using skirt-on-liner configuration
  - FIB (focused ion beam) microscopy of the microstructure of tribo-films (amorphous/crystalline)
  - In-situ friction measurements on single cylinder diesel engine
  - Correlate coating adhesion properties with residual stress properties and deposition parameters

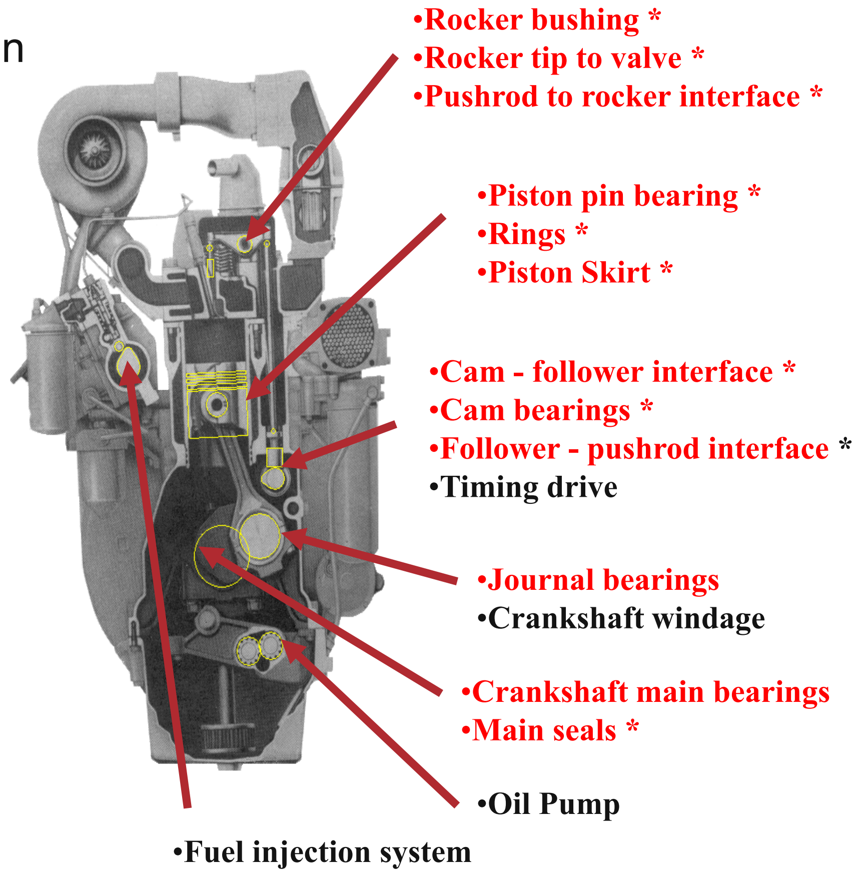
Accomplishment - Detailed studies of heavy-truck friction losses based on mechanistic models of boundary and hydrodynamic friction predict impact of lowering boundary friction and lubricant viscosity on fuel economy

- 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)

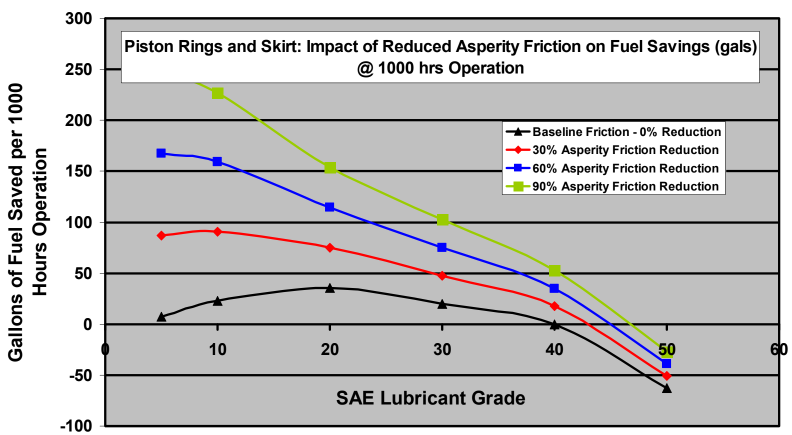


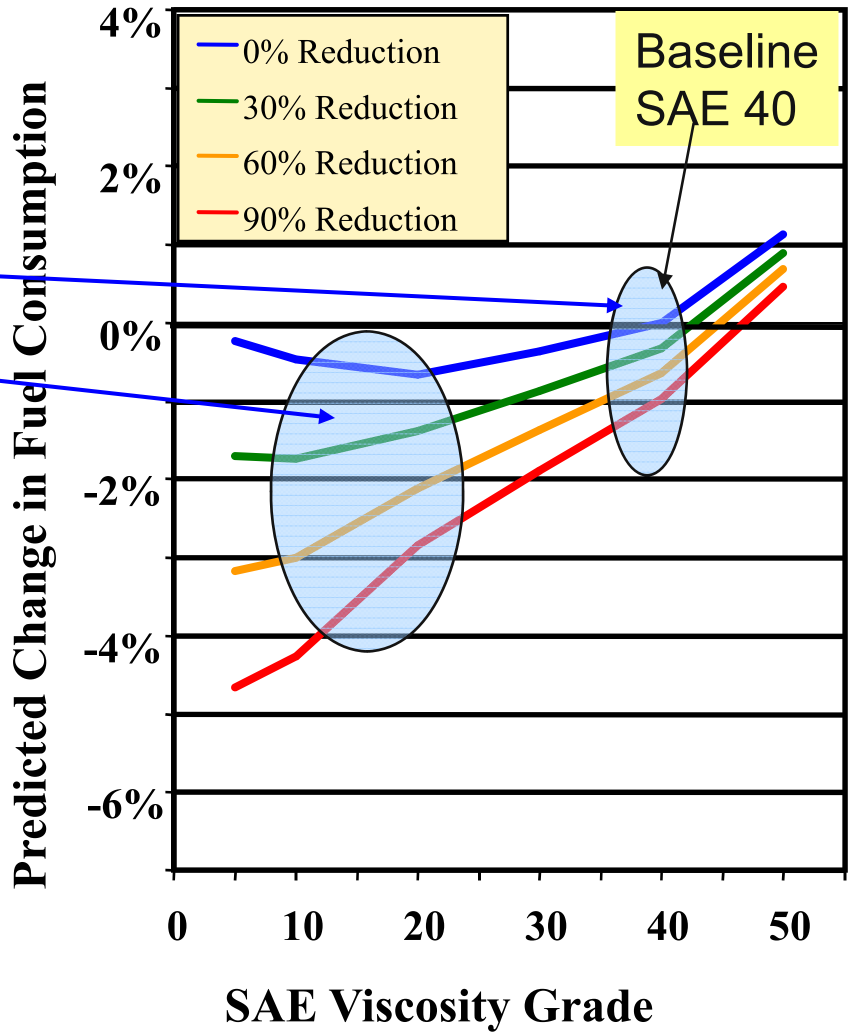
* interface considered in current study

Further details - VSS17 - Parasitic Energy Losses

Accomplishment - Modeling the impact of friction on fuel efficiency and identifying critical components - HD diesel

- **Prediction/Modeling of Fuel Savings**
  - Systematic studies on the effect of boundary friction and oil viscosity on fuel efficiency
  - Up to 1.3 % fuel economy improvement by low friction additives and/or coatings
  - 3-4% fuel economy improvement by reducing boundary friction and reducing oil viscosity, another 2-3% for drivelines
  - Model impact component-by-component to determine greatest ROI

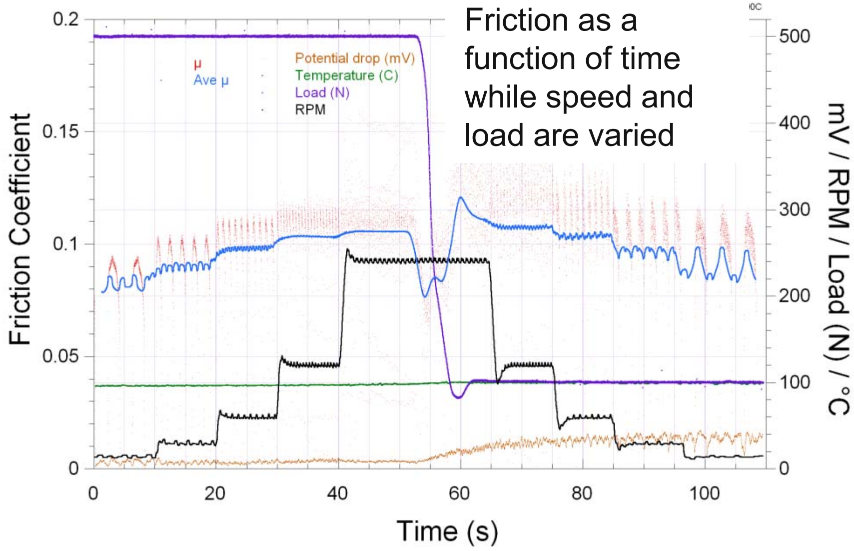


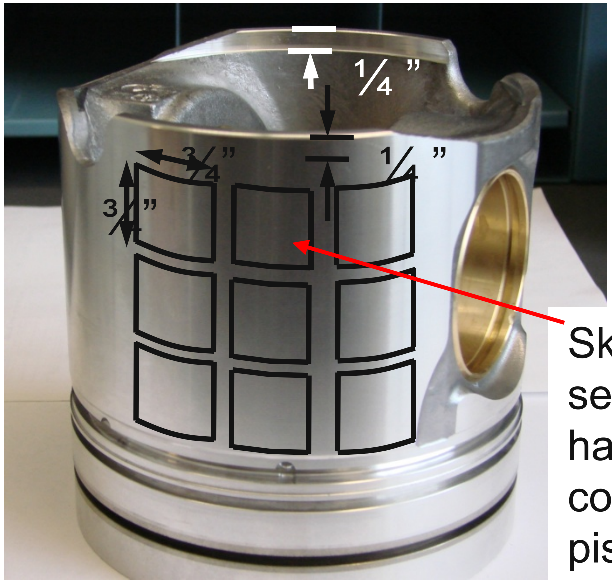


Further details - VSS17 - Parasitic Energy Losses

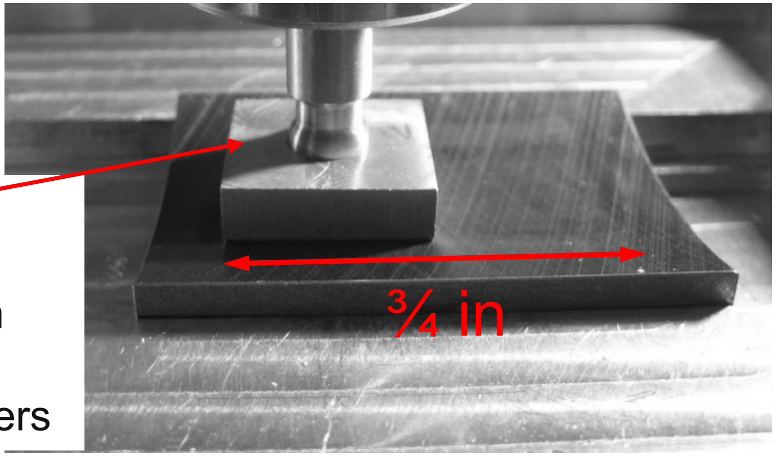
Accomplishment - Adapted ring-on-liner test rig to simulate piston-skirt-on-liner friction. Use segments of piston skirts sliding against cylinder liner segments

- Reciprocating test rig was modified and test protocols developed to test segments of piston skirts that reciprocate against liner segments. Loads and speeds selected to mimic in-situ tribological conditions



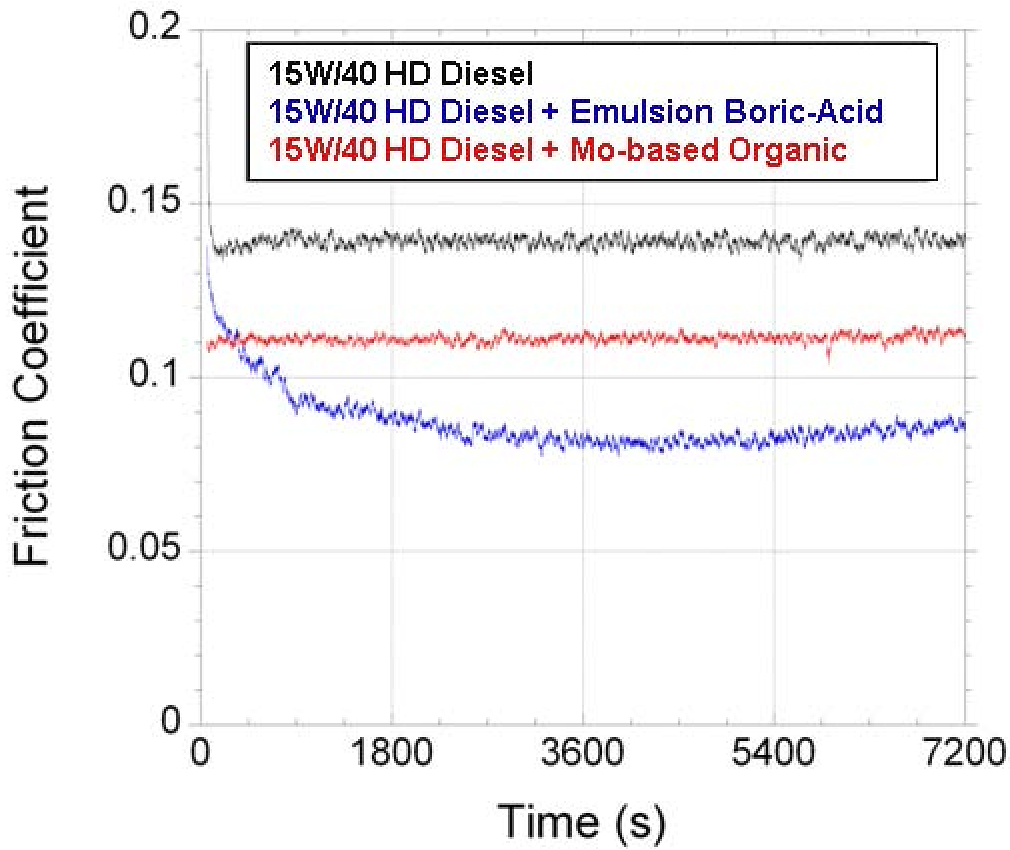


Skirt and liner segments harvested from commercial pistons and liners



Accomplishment - Demonstration of friction reduction in commercial diesel lubricant using an emulsion based boric-acid additive - 40 % reduction

- Skirt-on-liner tests
  - 105 C, 120 rpm, 250 N
- Boundary friction reduction
  - 20 % reduction for Mo based liquid additive
  - 40% reduction for an emulsion boric-acid based additive
- Additional details presented in VSS17 - Parasitic Energy Losses



Further details - VSS17 - Parasitic Energy Losses

Accomplishment - Single-cylinder engine at UM for piston-assembly friction measurement: Status of the Experimental Setup

- Designed and fabricated the instrumented liner for direct measurements of the piston-assembly friction force

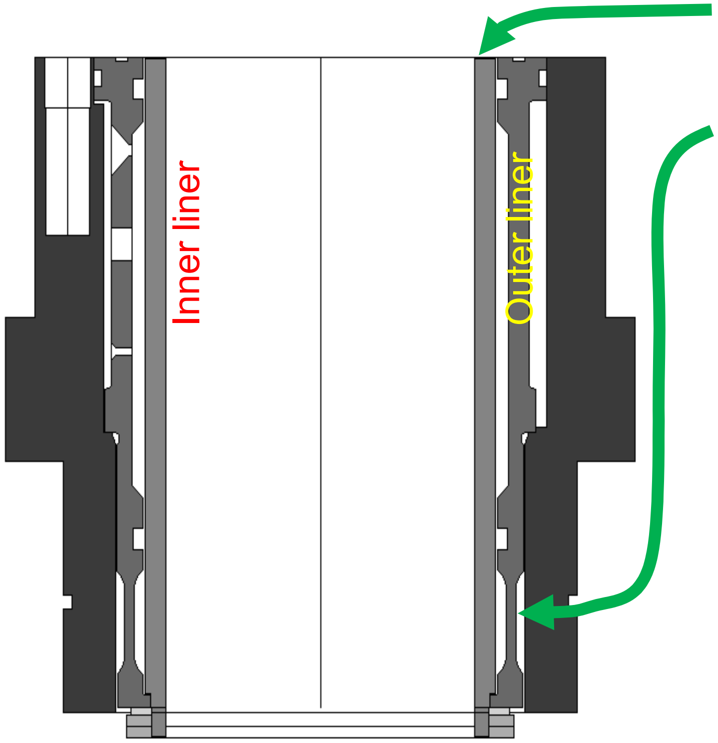
- Established a collaboration with MAHLE and obtained prototype steel pistons in order to create a configuration relevant for the medium and heavy-duty diesels

- Fabricated the new “jug” capable of accommodating the instrumented liner

- Worked with Ricardo to finalize the cylinder head assembly for future tests in a firing engine

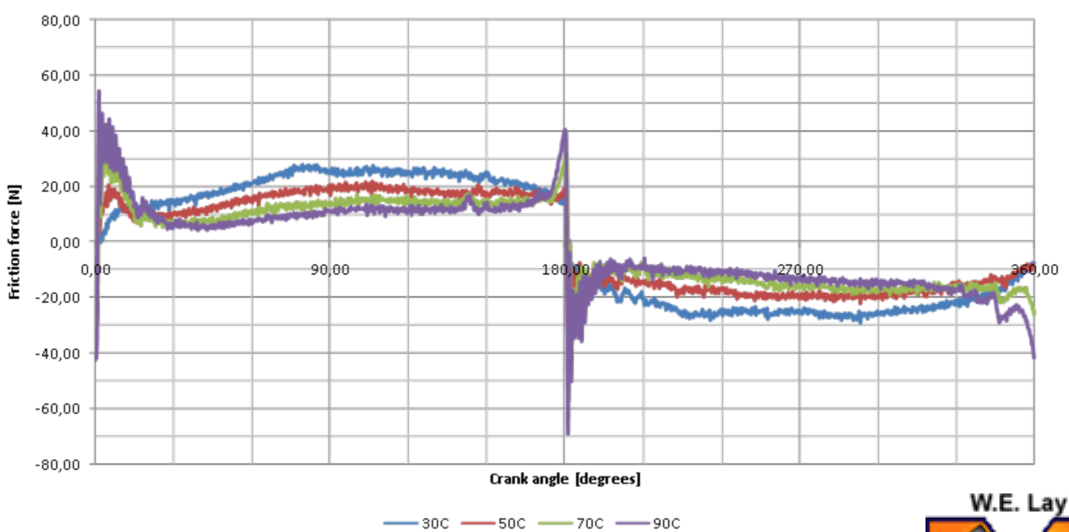
Accomplishment - Single-cylinder engine at UM for piston-assembly friction measurement: Methodology and Sample Result

- Pressure acting on the upper edge of the inner liner – measure with a piezo-electric transducer
- Force on the outer liner due to friction force on the inner liner and pressure – measure with strain-gages
- Subtract the pressure force from the total to get friction

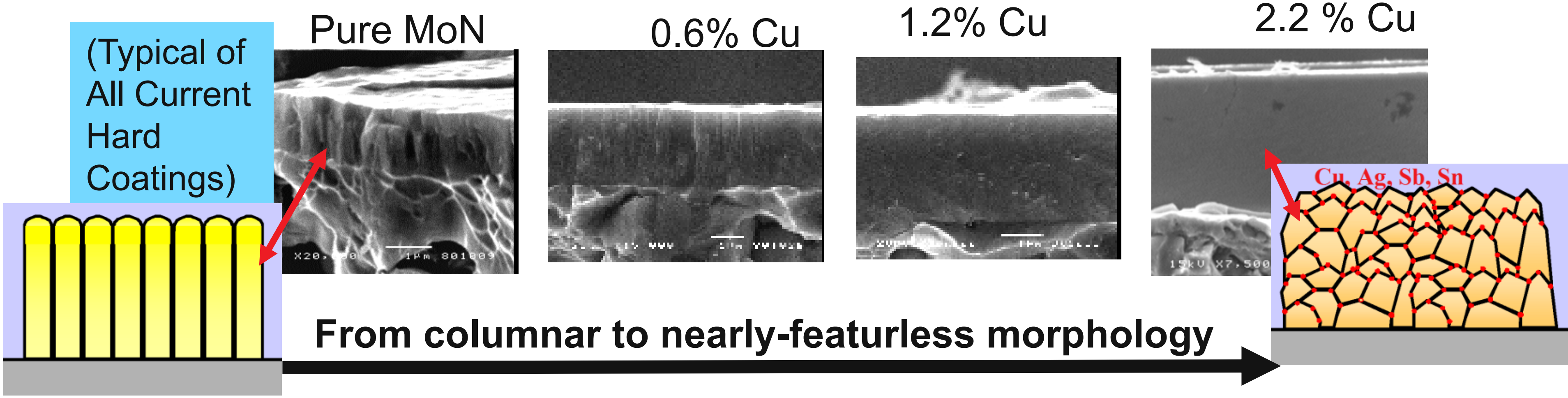


$$F_{friction} = F_{strain\text{-}gage} - F_{pressure}$$

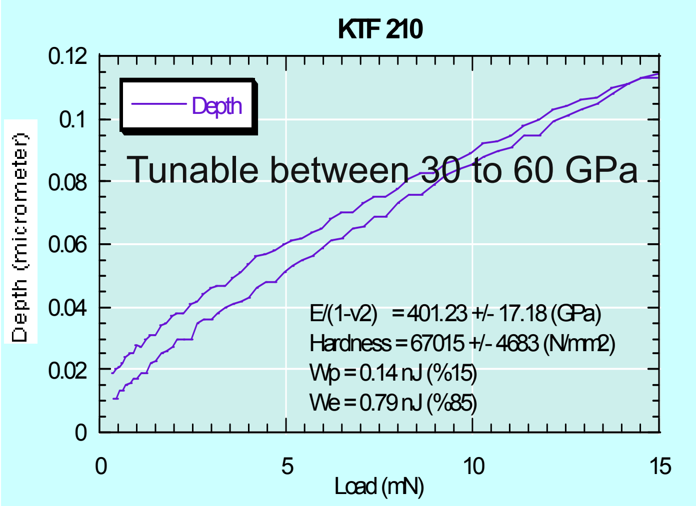
Sensitivity of the piston-assembly friction force to temperature (coolant and oil); 1000 rpm, motoring w/ open cylinder head



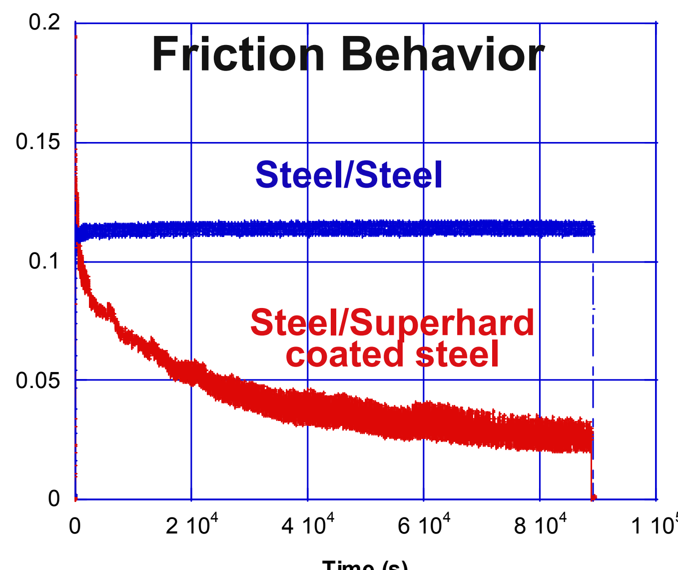
Accomplishment - Engineered a class of superhard (30-60 GPa), low friction coatings - 75% reduction in friction



Hardness Behavior



Proper selection of alloying elements and deposition conditions produce dense, superhard nanocomposite coatings that synergistically react with lubricant additives to provide low friction.



Further details - VSSP04 & PMP04 - Low-Friction, Hard Coatings

Accomplishment - Collaborating with equipment OEMs to transfer Superhard nanocomposite technology to industry

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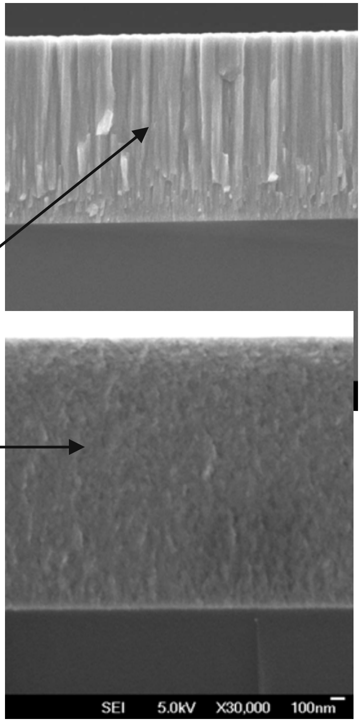
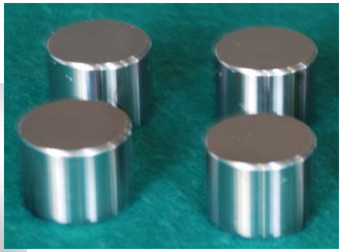
- Collaborating with equipment OEMs to demonstrate superhard nanocomposites can be produced on commercial systems.
  - Initial tests with industry produced weaker columnar microstructure, however, dense, equiaxed nanocomposite microstructure was achieved after recommendations by Argonne staff were followed.



- Currently collaborating with automotive OEMs and suppliers to treat engine components with low-friction hard coatings and evaluate them in engine and vehicle tests



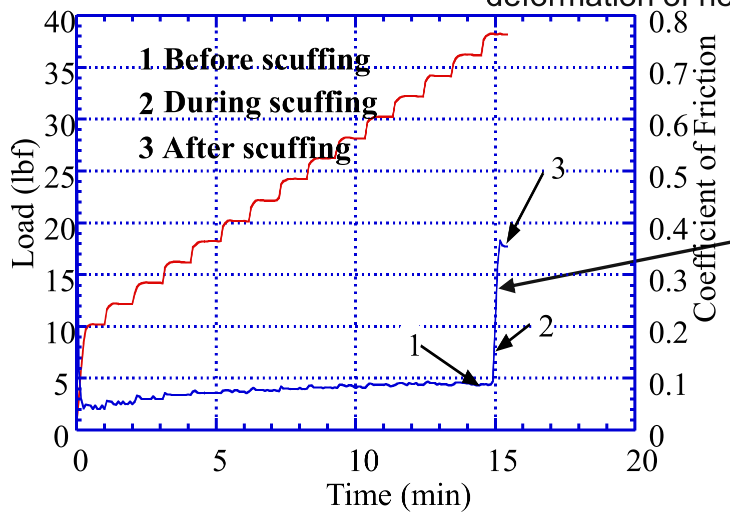
Further details - VSSP04 & PMP04 - Low-Friction, Hard Coatings

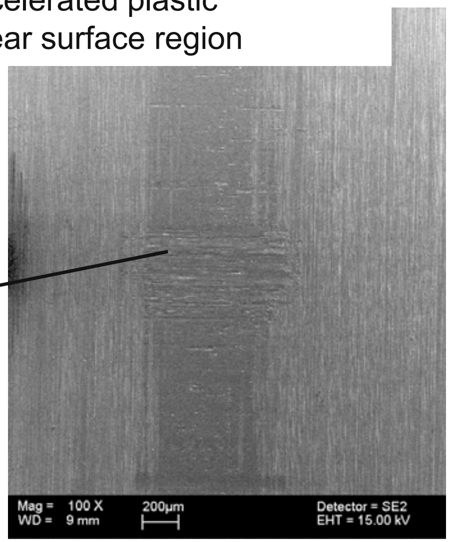
Accomplishment (BLL) - Developing Models of Fundamental Friction, Wear, & Durability/Reliability

- Reliability, durability, and friction depend on **surface** (formation of protective tribo-films) and **subsurface** (work hardening and thermal softening) phenomena.
  - **Phase 1** of project developed models of **subsurface** phenomena that control scuffing
    - *competition between work hardening and thermal softening determines onset of adiabatic shear instability leading to **scuffing***
  - **Phase 2** of project focusing on role of **surface** phenomena (tribo-film formation and coatings)

- Developed model based on fundamental material properties to predict on-set of **scuffing** – the most common mode of component failure. Verified model using ANL Advanced Photon Source.

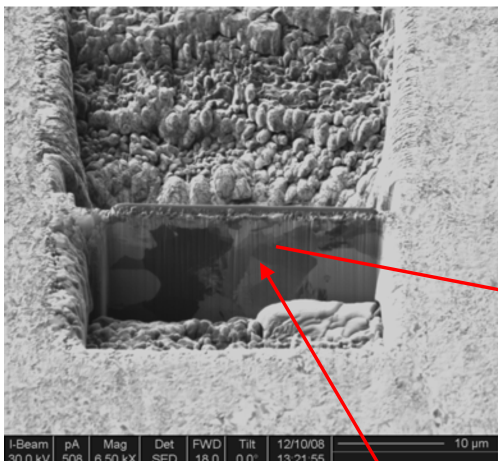
Onset of scuffing denoted by rapid increase in friction and accelerated plastic deformation of near surface region





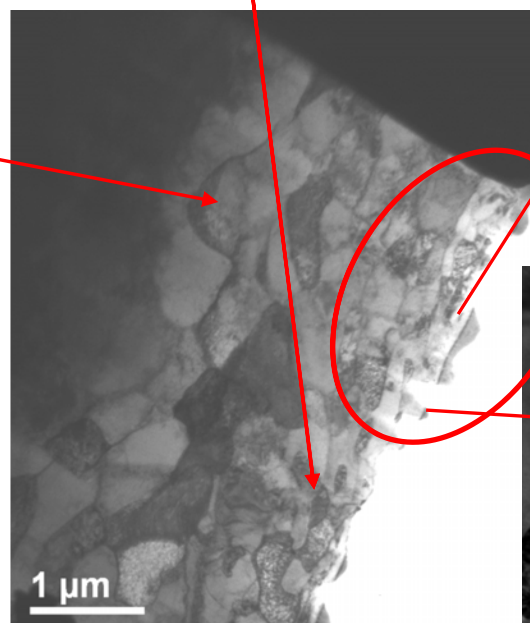
Technical Accomplishment - Demonstrated ability of focused-ion-beam (FIB) microscopy to image ultrathin tribo-films

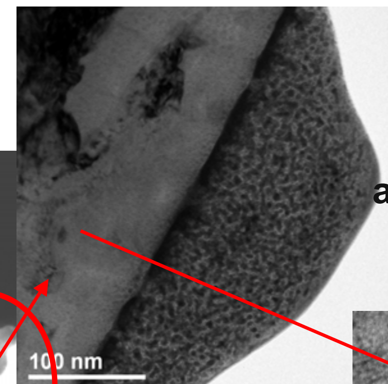
- FIB technique was employed to image ultrathin tribofilms produced during lab tests. With this technique it should now be feasible to understand the role of tribofilm microstructure and composition and apply this knowledge to models of tribofilm formation and their impact on protecting engine components - more precisely determine how tribofilms protect surfaces

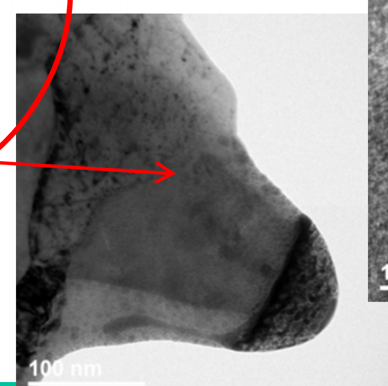


Harvest thin, electron transparent cross-sections of near surface regions for high resolution TEM surface & subsurface regions

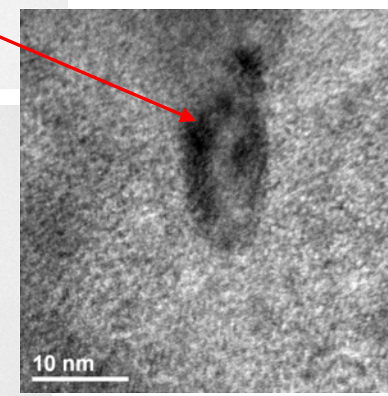
sub-surface grain refinement/work hardening







nanocrystalline feature in amorphous glassy tribofilm

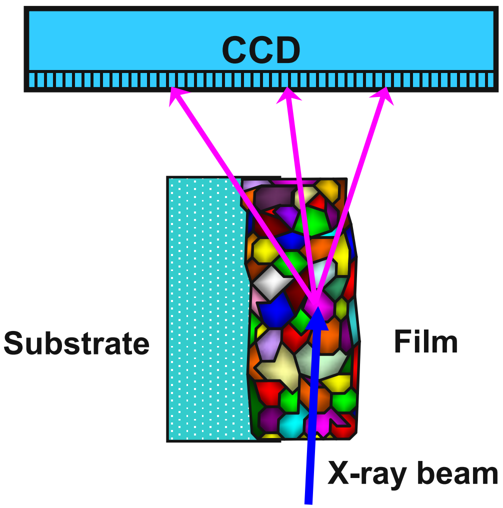


Further details - VSSP01 - Boundary Layer Lubrication

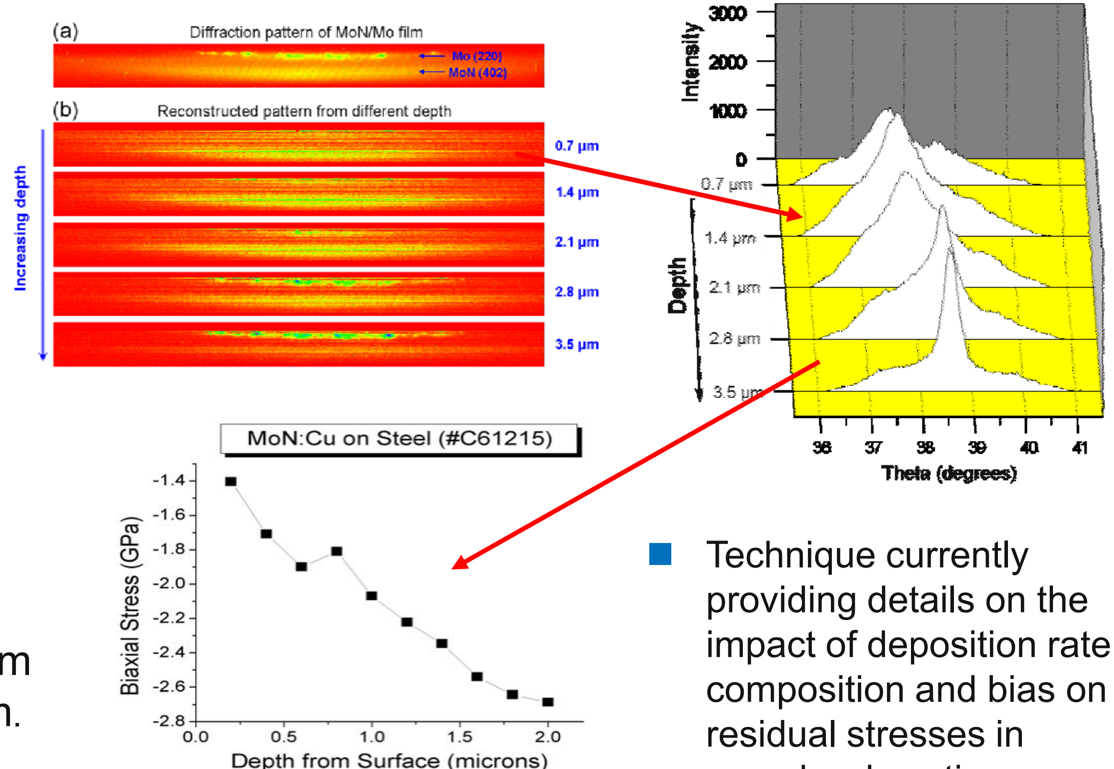
Technical Accomplishment - Developed and refined x-ray microdiffraction technique to quantify residual stresses in thin films as a function of depth

- Information on residual stresses in thin films is required to engineer coatings for high stress applications such as piston rings and valve components.
- The activities in this project demonstrated the ability to quantify the residual stresses in thin films as a function of depth with high resolution.

Cross-sectional microdiffraction



Scanning the cross section of a film using submicron mono x-ray beam.



- Technique currently providing details on the impact of deposition rate, composition and bias on residual stresses in superhard coatings

Collaborations

- Projects involve significant level of collaborations with academia and industry through WFOs and collegial agreements.
  - Boundary Layer Lubrication
    - *Caterpillar, Eaton, Lubricant and Additive OEMs, UIUC, and NU, TARDEC*
  - Parasitic Energy Losses
    - *Ricardo, U-Michigan, Mahle, Additive suppliers, TARDEC (FED- Fuel Economy Demonstration - HUMVEE)*
  - Low-Friction Hard Coatings
    - *Equipment OEMs, part suppliers, automotive OEMs*

- See individual project reviews for more details

Summary

- Models and studies indicate 10 to 15 % of petroleum used for on-road transportation is consumed by engine and driveline friction - more than the energy delivered to the wheels. Stringent emission policies and demand for high-performance powertrain components present new challenges for current tribological systems.
- The cluster of friction and wear reduction projects address critical issues related to reducing engine and driveline friction while maintaining or improving component reliability and durability under challenging tribological environments.
- Mechanistic models of engine friction were developed to predict the impact of boundary friction and lubricant viscosity on fuel consumption - studies suggest improvements in fuel efficiency up to 3-5 % are feasible through advanced engine tribological strategies, and another 2-3% with improved driveline technologies.
- Advanced lab-simulation studies have identified several promising strategies to provide the level of boundary friction reduction required to enable the use of low-viscosity fluids
- Advanced technologies have been identified and developed that demonstrate not only significant friction reduction, but also significantly improved wear-resistance
- Advanced analytical techniques (FIB, ion beam analysis, x-ray diffraction) are providing detailed information on tribological failure phenomena that are being used to develop failure models
- Together, the projects are providing the science and technologies required to engineer advanced tribological systems required to reduce conserve energy and improve performance

Path Forward (major milestones/goals for FY09/10)

- Boundary Layer Lubrication
  - Develop technique to measure real contact area temperature of lubricated interface.
  - Measure nano-mechanical and friction properties of low-friction boundary films
- Parasitic Energy Losses
  - Single cylinder engine validation of friction models and lab-simulations
  - Continued evaluation of candidate strategies (coatings and additives)
    - *Ring AND skirt tests*
  - Modeling of accessories (fuel delivery system, oil and water pumps, etc.)
  - Apply approach to determine impact of friction on ‘carbon footprint’
- Low-Friction Hard Coatings
  - Production and scale-up of superhard nanoncomposite coating technology
- X-Ray Residual Stresses
  - Application of microdiffaction technique to commercial coatings
  - Correlations of residual stress state with film./coating adhesion