Development of High Power Density Driveline for Vehicles
(Developing enabling tribological Technologies)

O. O. Ajayi, C. Lorenzo-Martin, A. C. Greco, and G. R. Fenske

Argonne National Laboratory

2015 Annual Merit Review

June 9, 2015

Project ID # VSS058

Overview

Timeline

- Start date - October 2010
- End date - FY2015
- Percent complete – 90%

Budget

- Total project funding
  - DOE share – 870K
  - Contractor share – 120K (in-kind)
- Funding
- FY 14 – 235K
- FY15 – 65K

Barriers

- Barriers addressed
  - Constant Advances in Technology
  - Computational models, design and simulation methodologies
  - Risk Aversion
  - Cost

Partners

- Interactions/ collaborations
  - Wedeven Associates, Inc.
  - Afton Chemical Corp.
  - Infineum USA L.P.

Project Objective and Relevance

- **Objective:** The ultimate objective of this project is to achieve significant vehicle weight reduction through reduction in size and weight of the driveline systems (20% of vehicle weight)such as transmission, axle.

- The driveline size reduction to be achieved by developing materials, surface and lubrication technologies for increasing the power density of the systems.
  - Can enable downsizing of power-train system without loss of performance
    - Further improvement in fuel savings

	% Improvement in Fuel Economy / % Weight Reduction EPA Combined (Metro-Highway) Drive Cycle			
	Passenger Vehicle		Truck	
	Base Engine	Downsized Engine	Base Engine	Downsized Engine
Gasoline	0.33%	0.65%	0.35%	0.47%
Diesel	0.39%	0.63%	0.36%	0.46%

Project Focus and Expected Outcome

- Identify, develop, integrate and evaluate materials, surfaces and lubricant technologies that will ensure adequate wear, scuffing and contact fatigue life for high power density gearbox system.
  - Requirements are often contradictory – approaches used to increase one attribute usually degrades another

- Integrated materials, surface and lubricant technologies that will simultaneously increase wear, scuffing and contact fatigue life under severe contact conditions.
  - For 20% weight reduction in gear box
    - Requires 2X increase in wear life
    - 2X increase in scuffing life
    - 3X increase in contact fatigue life

FY14 and FY15 Project Milestones

Month/Year	Milestone
09/14	Complete scuffing performance evaluation of integrated surface and lubricant technologies for HPD contacts (completed)
09/15	Complete contact fatigue performance evaluation of coatings and lubricant technologies (In progress)
12/15	Issue a report documenting highlight of the finding and technologies developed in the project

Technical Approach/Strategy

- To establish materials, surface and lubricant technologies target and goals , analyses must be conducted to
  - Determine gear contact kinematics for gearbox with different levels of size reduction in a planetary gear system
  - Determine impact of new contact parameters on gearbox reliability and durability
    - Wear, scuffing and contact fatigue (pitting) life reduction

- Evaluate performance of some of the existing materials, surface (texture, coatings, treatments…..), and lubricant technologies and their combinations to mitigate reliability and durability issues of high power density (HPD) gearbox.

- Develop and evaluate appropriate surface and lubricant technologies as needed to simultaneously enhance wear, scuffing and contact fatigue life of gears and bearings.
  - Often contradictory

Technical Accomplishment and Progress

- Highlights of Previous accomplishments
  - Based on gear contact kinematics, defined the required levels of wear, scuffing and contact fatigue requirement for different levels of size reduction.
    - 20% size reduction requires 2X increase in wear life, 2X increase in scuffing life and 3X increase in contact fatigue life.
  - Identified, lubricant and coatings and combination of both providing 3 – 5X increase in wear life.
  - Developed a low viscosity lubricant formulation that reduced friction in boundary lubrication regime and provide 4X increase in wear life
    - **Pate**nt pending
  - Demonstrated 2 – 3X increase in scuffing life with the use and lubricant technologies

Technical Accomplishment and Progress:
Contact Fatigue performance evaluation

- Industry and standard evaluation of contact fatigue for gear is the twin roller test

Run each test under constant condition of load, speed and temperature until failure. 8 - 12 tests per group

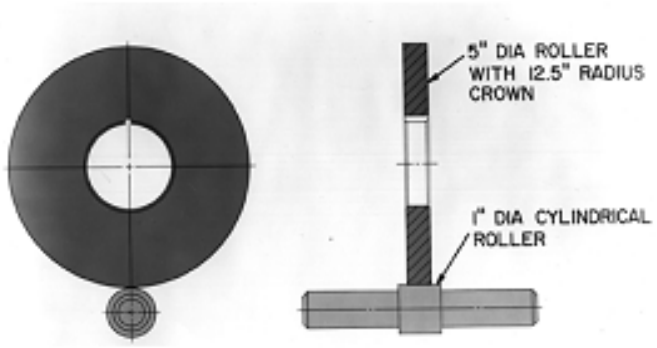
Test parameters:

Stress -- 2.4 - 3.4 GPa

Lambda -- 0.2 - 0.5

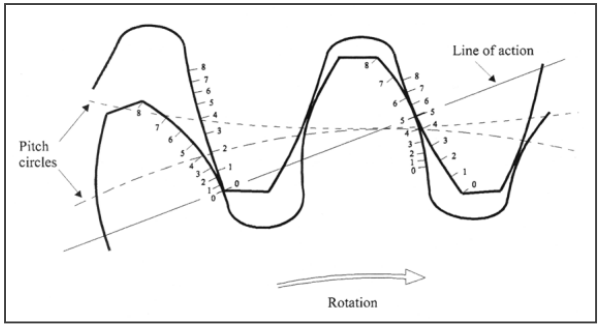
Sliding -- 21%

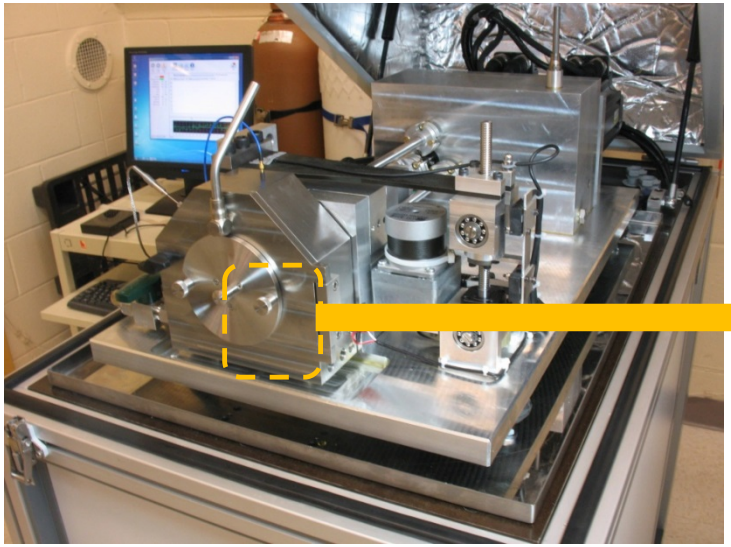
Temperature -- 90 - 105 C

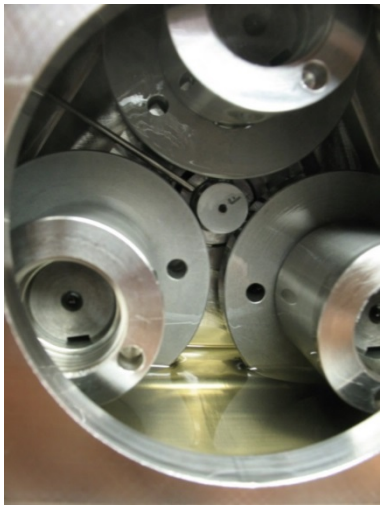


Weibull analysis to determine characteristic pitting life.

pitting Test Rig
PCS Instruments







Roller contact kinematics same as a meshing gear teeth

Operating Conditions:
- Load: Up to 1250 N (~3 GPa)
- Speed: Up to 4 m/s
- Slide-to-roll: 0% (pure rolling) to +/-200% (pure sliding)
- Temperature: ambient to 135° C

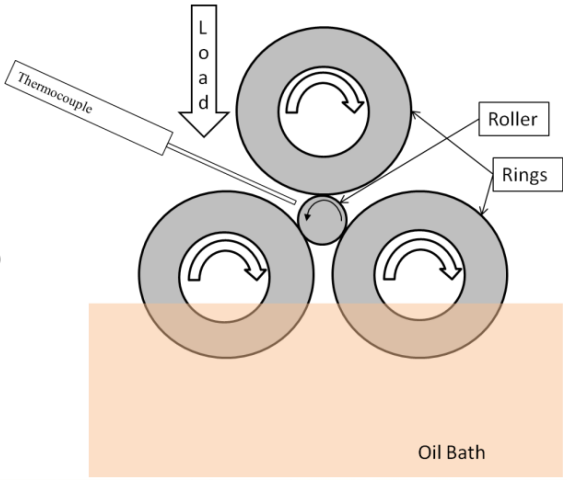


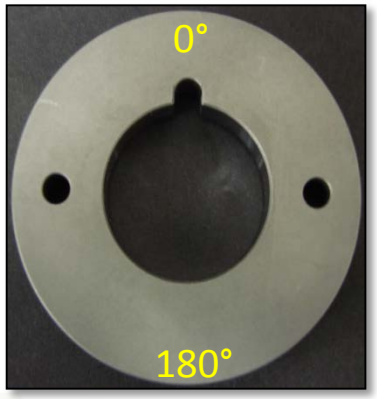
Figure 2: Diagram of MPR layout.

Contact fatigue test Parameters

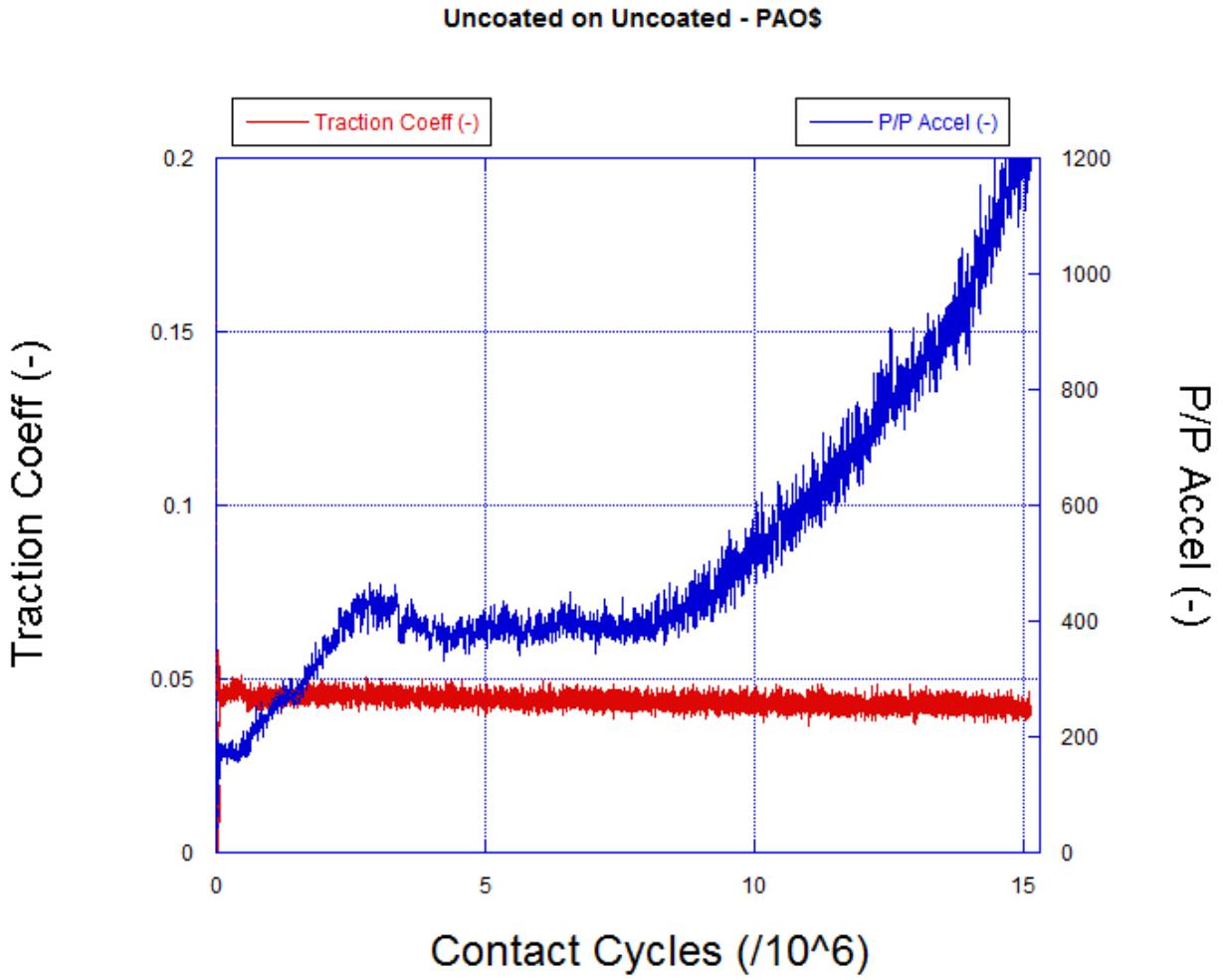
Test parameters and conditions identified to produce satisfactory contact fatigue damage mode -

- Periodic inspection of surfaces to assess damage mode.

- Ring and Roller Material = AISI 52100
- Temperature = 55° C
- Velocity = 3 m/s
- Load= 430 N (2 GPa Contact pressure)
- SRR = 40%
- Oils =PAO4 basestock, ANL-PF, Fully formulated commercial transmission oil.



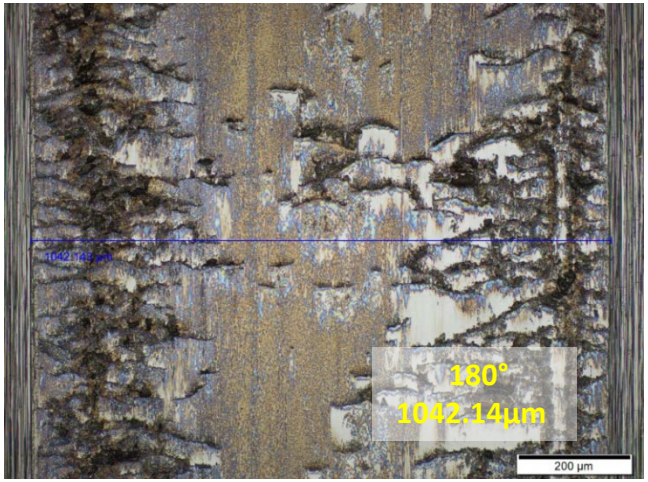
Uncoated roller tested with basestock oil -



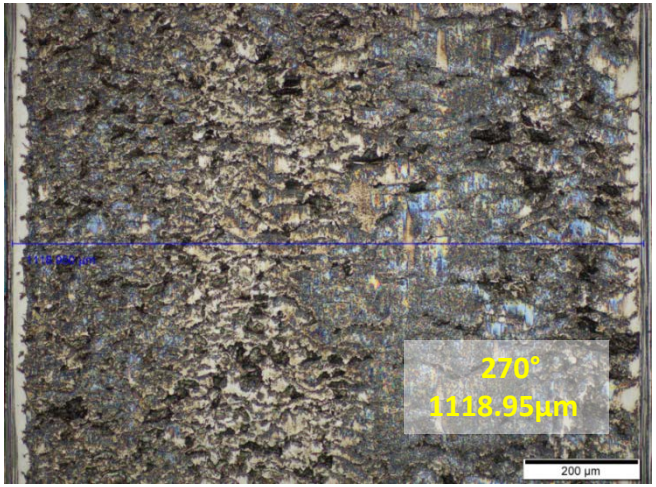
Steel on Steel

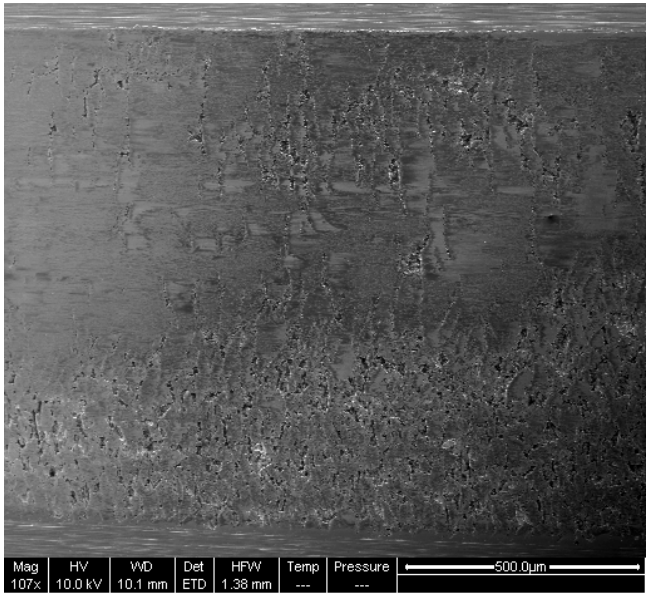
Failure point defined by P/P Accel. Greater than 1200
- 15 million cycles

Uncoated Roller with baseline lubricant

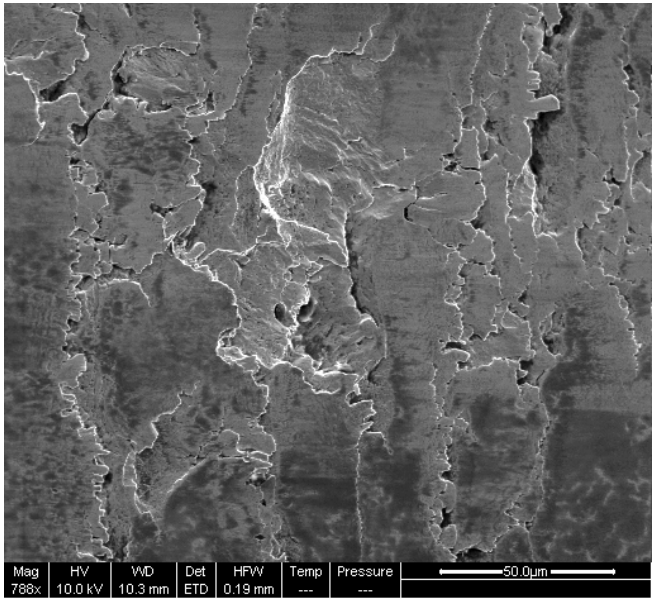


Optical micrograph

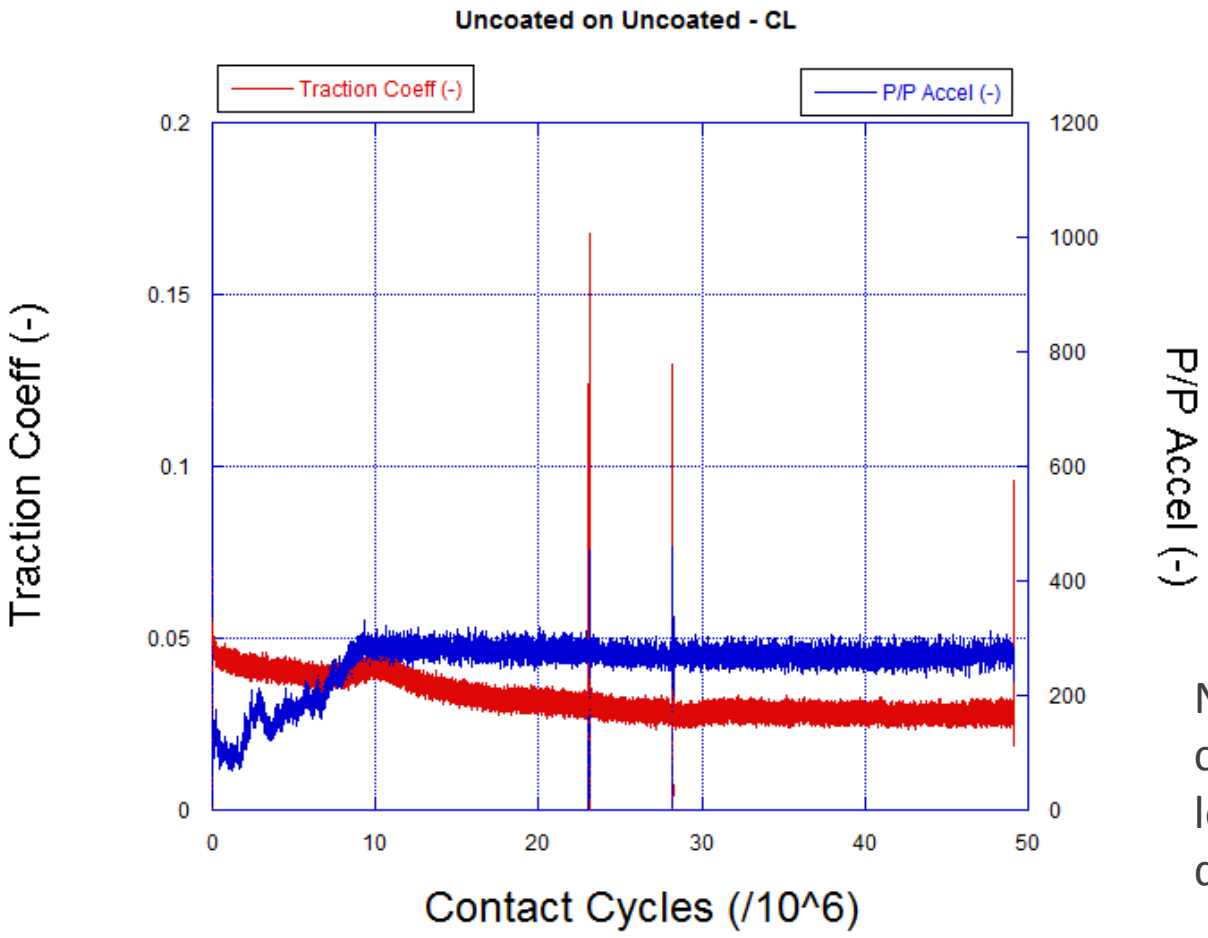


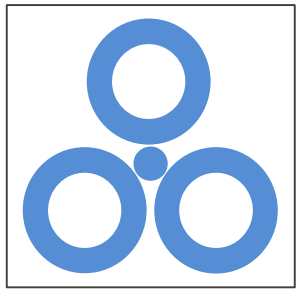


SEM micrograph



Uncoated fully formulated transmission oil



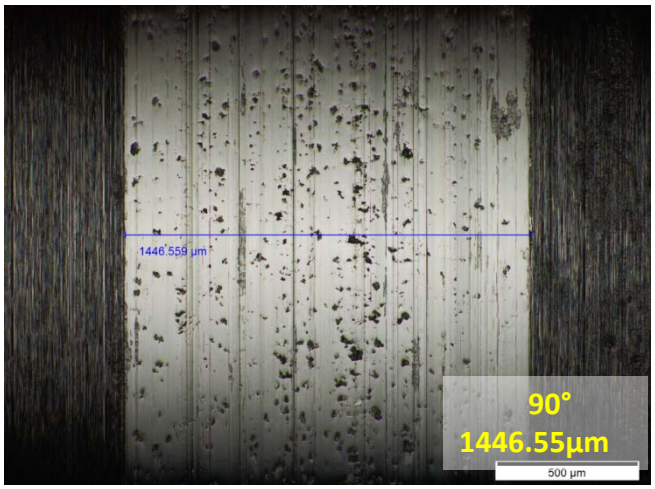


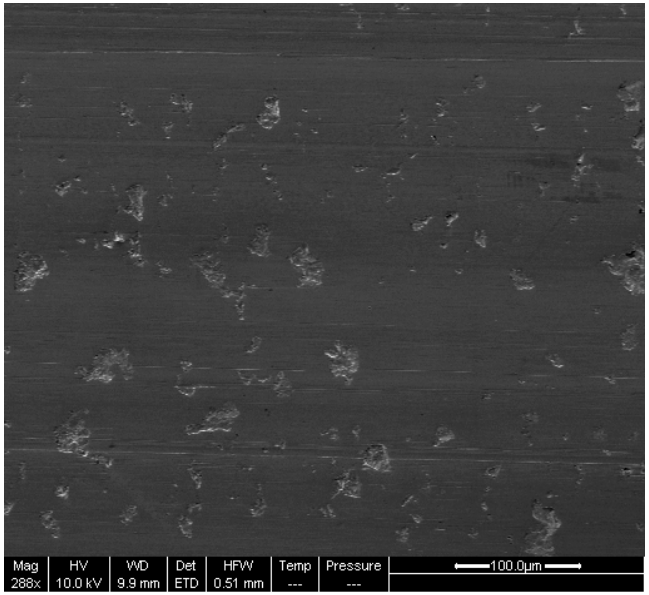
Steel on Steel

No failure after 50 million cycles, but enough wear leading to noticeable dimensional change

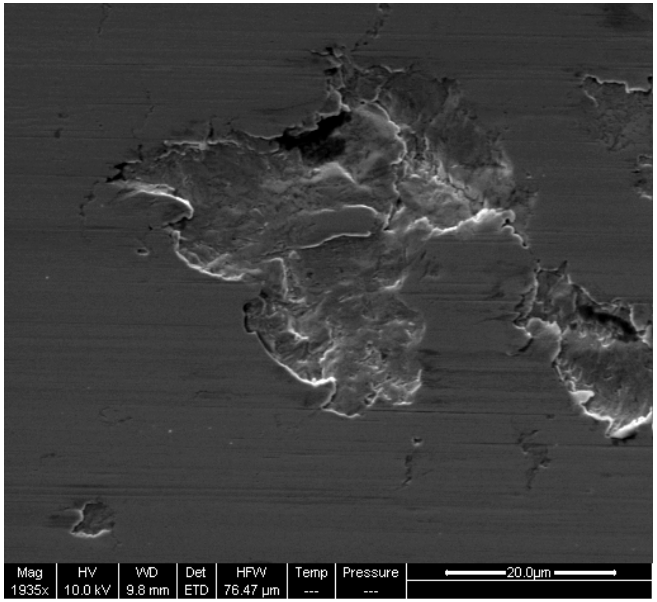
Uncoated fully formulated transmission oil

Optical micrograph

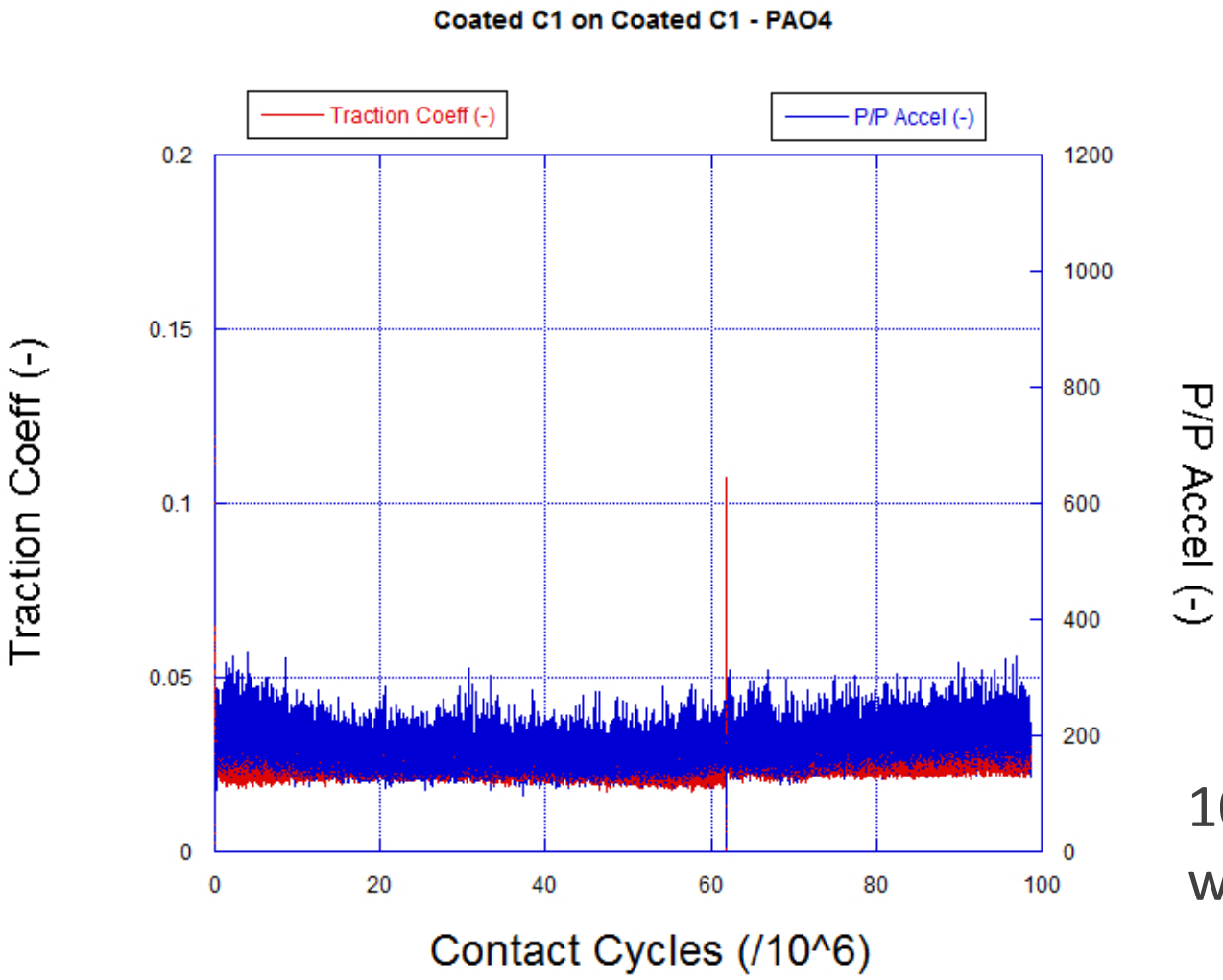




SEM micrograph



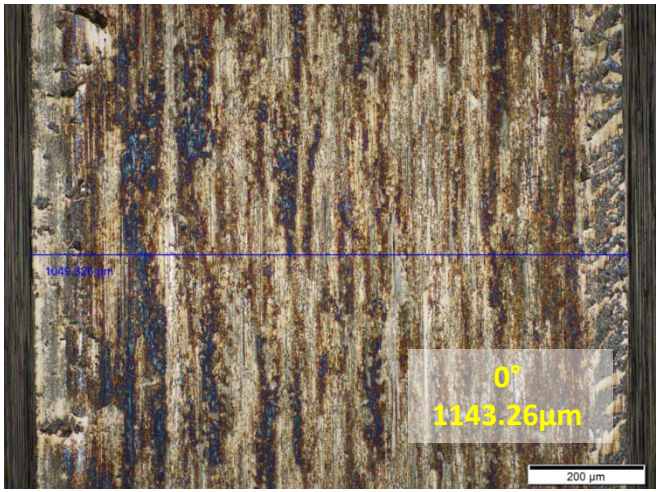
Coated samples tested with basestock oil



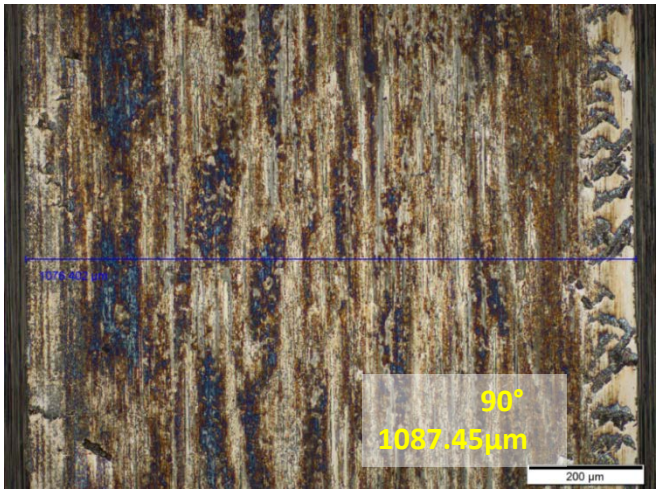
Coated Roller and Rings

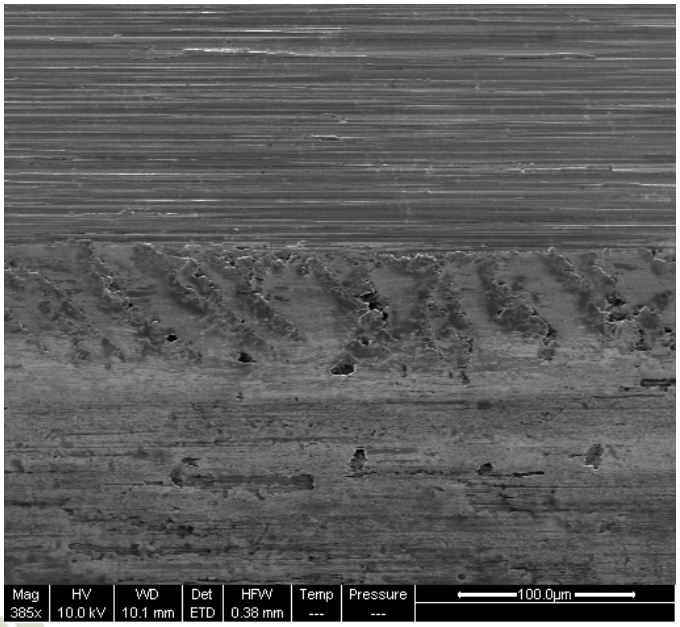
100 million cycles with no failure

Coated samples tested with basestock oil

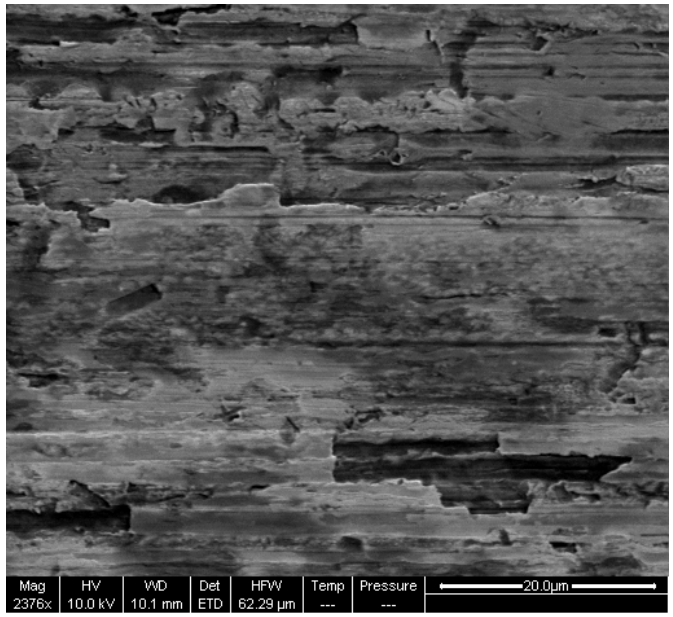


Optical micrograph

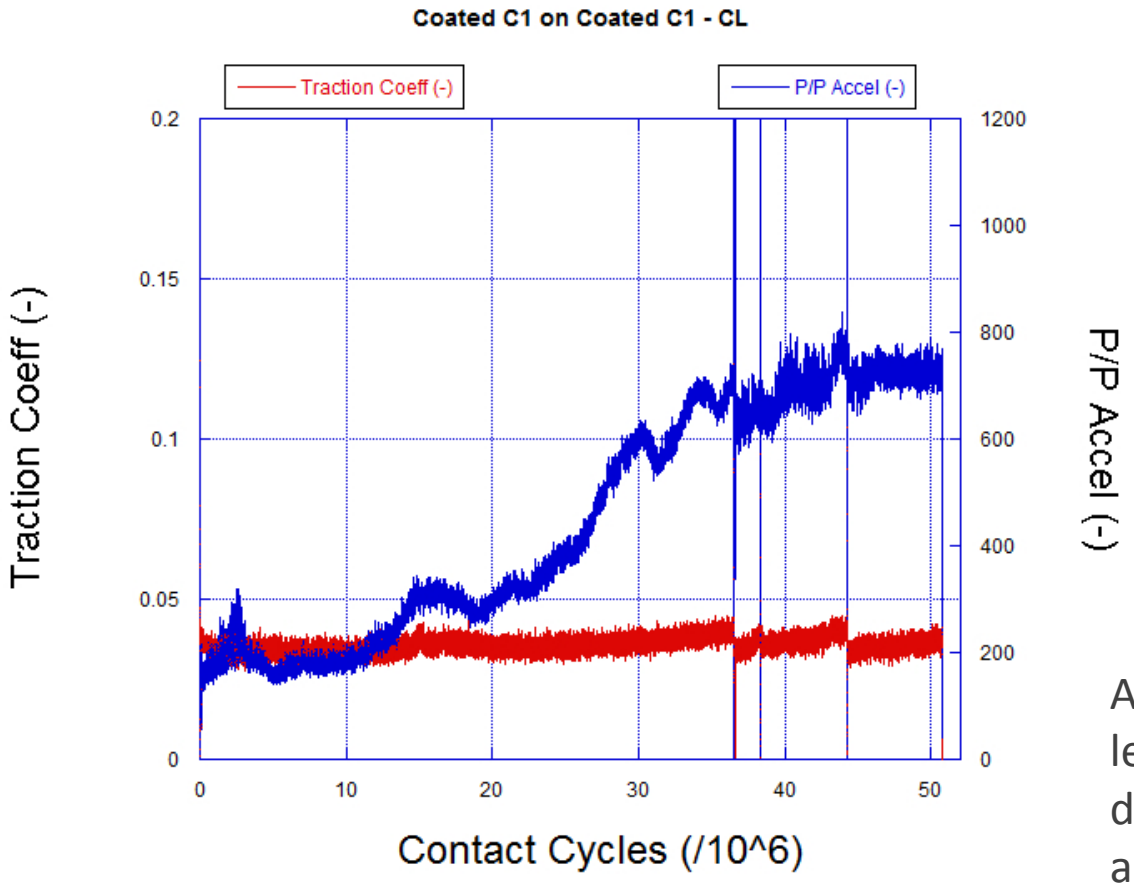


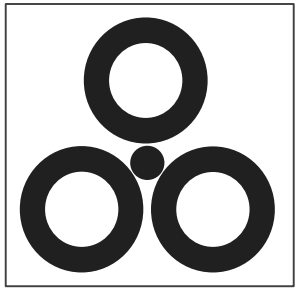


SEM micrograph



Coated specimens with fully formulated transmission oil

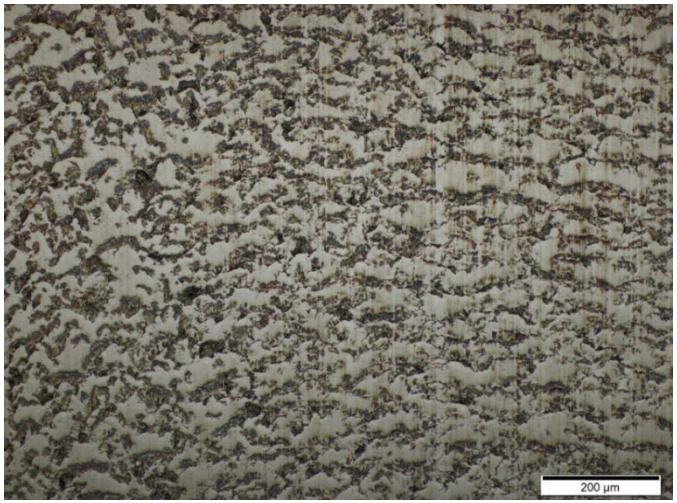




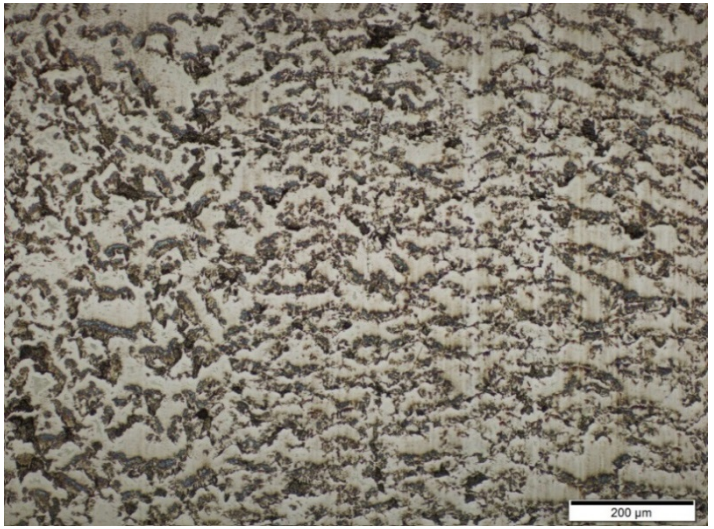
Coated Roller and Rings

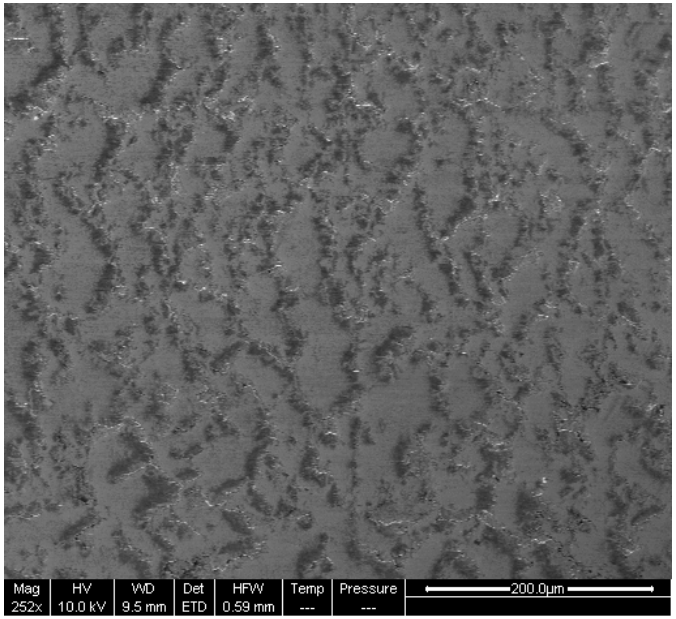
Although P/P Accel signal was less than 1200, enough surface damage to declare failure at about 50 Million cycles.

Coated specimens with fully formulated transmission oil

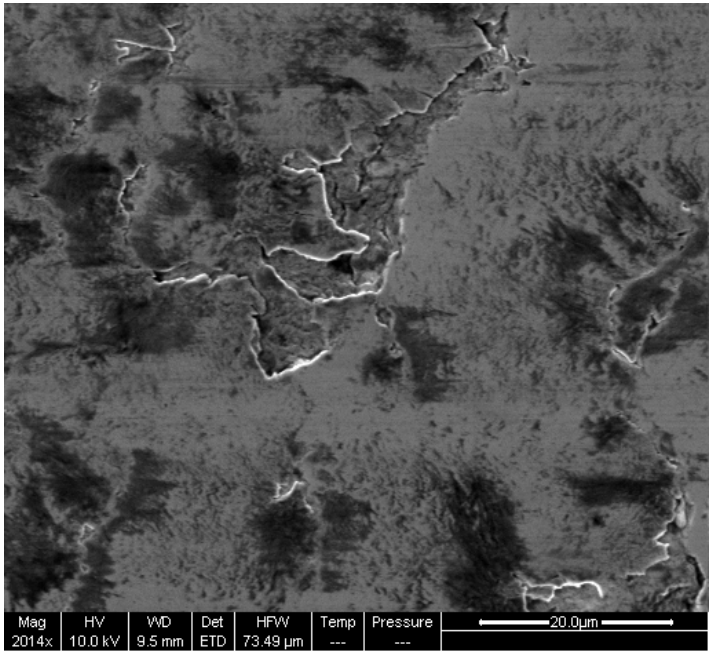


Optical micrograph



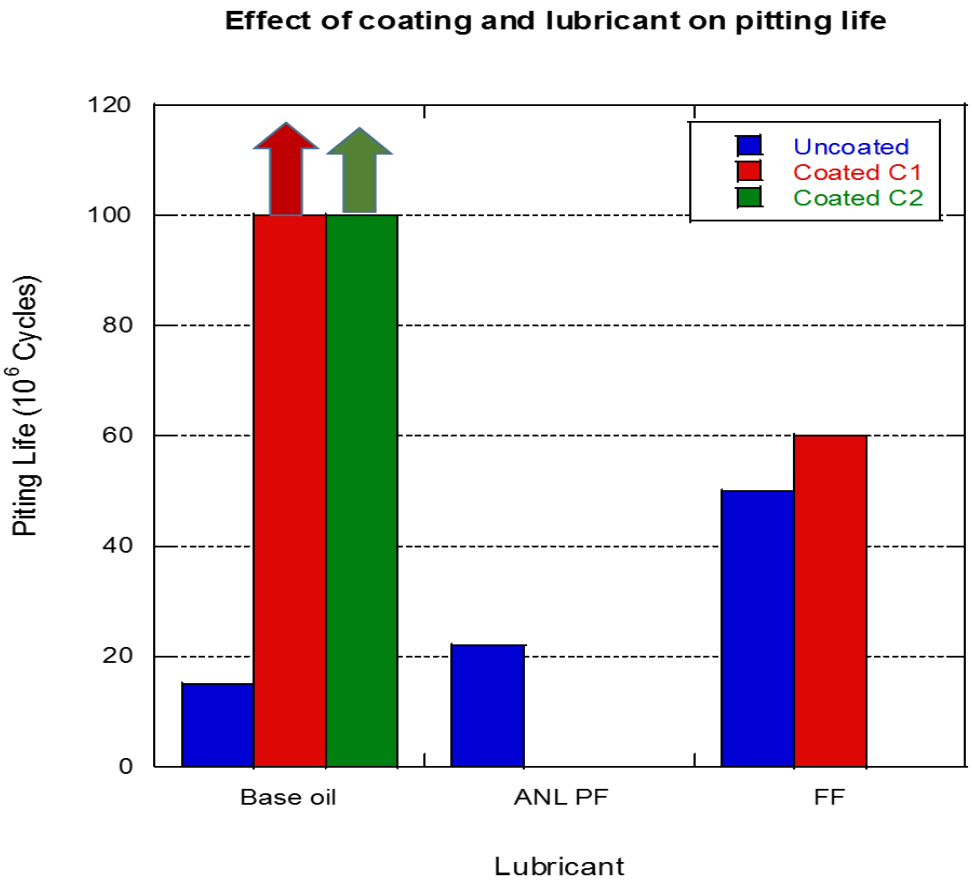


SEM micrograph



Summary of Preliminary evaluation of Pitting Life

- Both coatings and lubricant technologies can provide significant improvement in contact fatigue or pitting life
- Combination of both technologies sometimes detrimental to contact fatigue life



Previous review comments and issues

- All the reviewers agreed the work supports DOE mission but ignored the bending and noise requirement in gears.
  - Response: We fully agree with the need and potential benefit of the work. While we recognize the bending fatigue and noise requirements, these are outside the scope of the present project. There is no doubt need to address these other performance requirements.
- Some of the reviewers raised the question of the impact of ANL lubricant on contact fatigue life in view of its excellent impact on scuffing and wear
  - Response: Although there was not enough time and resources to conduct comprehensive contact fatigue performance evaluation for the lubricant (as the project ended), preliminary evaluation showed that the lubricant provided only a slight improvement in contact fatigue life.
- Reviewers will like to see more collaboration with gearbox and transmission manufacturers.
  - Response: ANL recently joined the Ohio State University GearLab consortium. We feel this will provide the necessary contacts and potential avenue for better collaboration with the appropriate stakeholders in the technology.

Collaborations

- **Wedeven Associates, Inc. (industry):**
  - Development of test methodology for gear teeth contacts
  - Evaluation and analysis of materials and lubricant technologies

- **Infineum USA L.P. (industry):**
  - Development of advanced lubricant additives for steel and thin film coatings to ensure adequate wear, scuffing and contact fatigue life

- **Other Potential Collaborators**:
  - DOE Wind Energy Program
    - Leverage efforts on wind turbine gearbox reliability projects
  - Other agencies with programs and projects on gearbox technology development.
  - Joined the OSU GearLab consortium consisting of about 72 members.
    - Avenue for better collaboration with industry stakeholders.

Summary

- In order to enable 20% size and weight reduction in high power density driveline system, simultaneous improvement in contradictory failure modes is needed
  - At least 2X increase in wear life.
  - At least 2X increase in scuffing life.
  - At least 3X increase in contact fatigue or pitting life
- With lubricant and coating technologies, demonstrated
  - 4-5X improvement in wear life
  - 2-3X improvement in scuffing life
- Initial preliminary contact fatigue life evaluation showed that coatings and lubricants can provide pathways to contact fatigue life improvement.
  - Some evidence of potential antagonistic interaction between coatings and lubricants with regards to pitting.