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

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Project ID # VSS058

Overview

Timeline

- Start date - October 2010
- End date - FY2015
- Percent complete – 70%

Budget

- Total project funding
  - DOE share – 870K
  - Contractor share – 120K (in-kind)
- Funding
- FY 13 – 365K
- FY14 – 235K

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

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

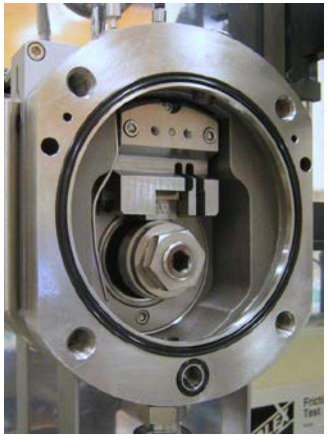
FY13 and FY14 Project Milestones

Month/Year	Milestone
06/13	Develop and complete performance evaluation of lubricant additive for friction and wear reduction (completed)
09/13	Complete friction and wear performance evaluation of coatings and lubricant combination (Completed)
12/13	Complete evaluation of impact of thin-film coatings on scuffing life of advanced gear materials (completed)
9/14	Complete scuffing performance evaluation of integrated surface and lubricant technologies for HPD contacts (In progress)

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
    - Patent pending

Technical Accomplishment and Progress - Scuffing Evaluation



- Scuffing test involves progressive increase of contact severity until failure –
  - Progressive increase in load
  - Progressive increase in sliding velocity
  - Progressive increase in temperature
  - Reduction of quantity of lubricant – starvation

- Block-on-ring scuffing test rig.
  - progressive increase in load
  - Scuffing is indicated by sudden rise in friction.

- Impact of lubricant and surface modification evaluated and quantified.

2X increase in scuffing life required for 20% size reduction

Technical Accomplishment and Progress - Scuffing Evaluation

Test materials:

- SAE 4620 ring (Rc 58-63)
- SAE tool 01 block (Rc 58-63)

Lubricant:

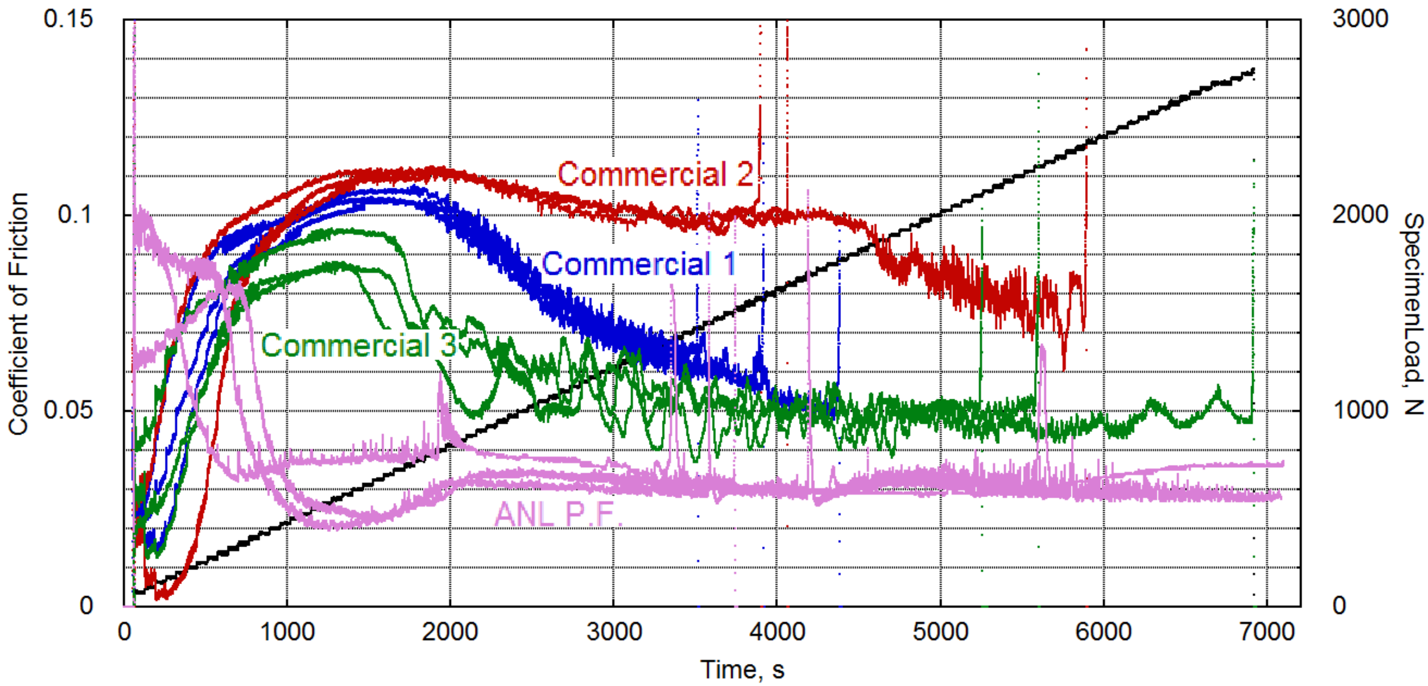
- 4 different advanced commercial gear oils
- ANL low viscosity formulation

Coatings information:

Name	Group	Composition	Deposition	Thickness measured (µm)	Thickness manufacturer (µm)	Hardness manufacturer
C3	Composites	CrN/CrC	PVD	3.83	1-5	2000-2200
C3S	Composites	CrN/CrC/(Mo, W)S_2	PVD	3.29	3-7	2000-2200
C7	Composites	TiAlSiCN	PVD	4.19	2-10	3200-3500
C10	Simple Coatings	DLC (ta-C)	PVD	1.07	0.5-2.5	5000-9000
C11	Simple Coatings	DLC(a-C:H)	PACVD	2.58	1-4	2000-3000
C12	Simple Coatings	Me-DLC	PVD	6.89	1-5	1000-2000
TiN	Simple Coatings	TiN	PVD	3.35	1-5	2300-2500
Tribologix	Non-vacuum Deposition	complex composite	sprayed	3.45		
NiPTFE	Non-vacuum Deposition	Ni + teflon®	electrochemical	8.05		

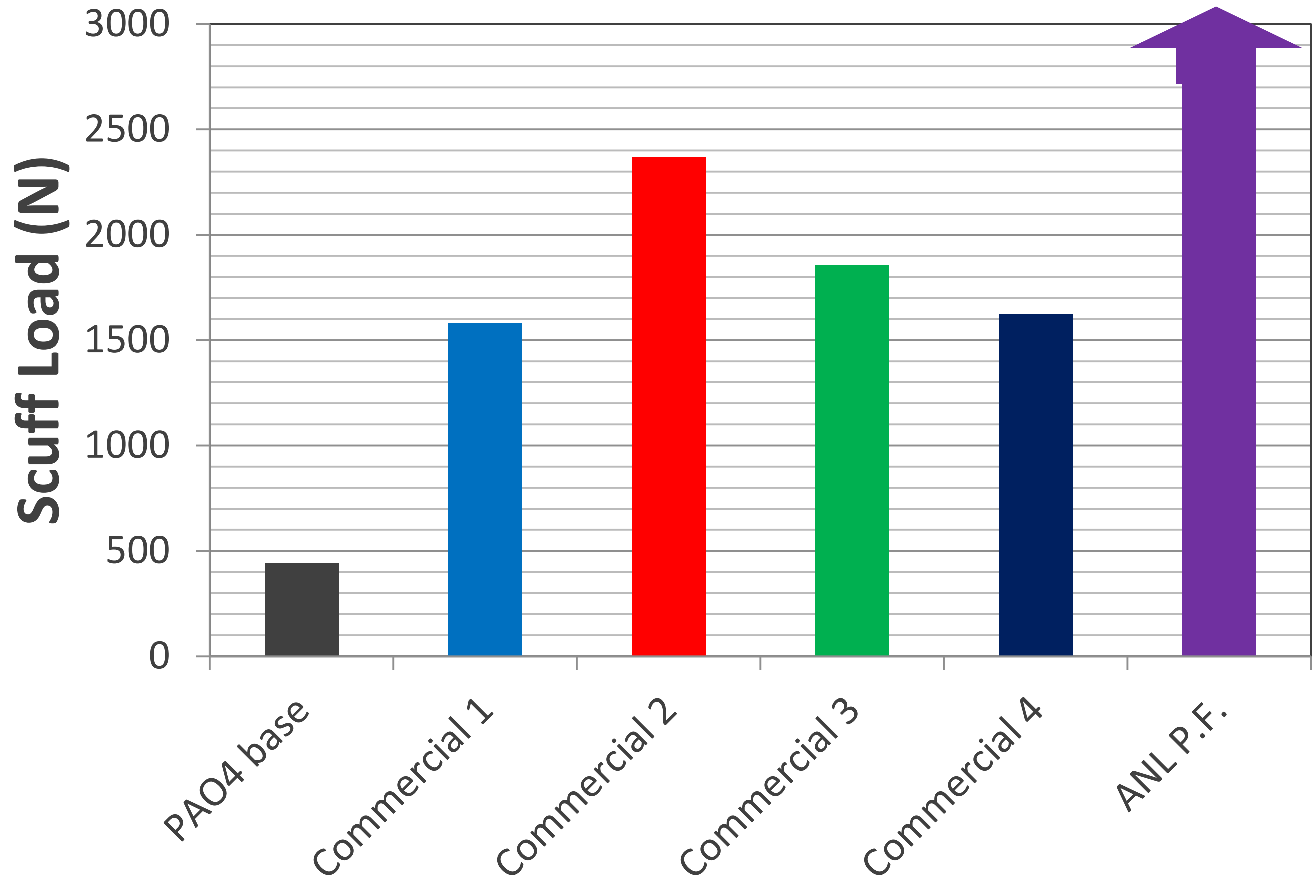
Effect of Lubricant on scuffing Life

- Frictional behavior of fully-formulated commercial gear oils and ANL formulation with increasing contact severity during scuffing test.



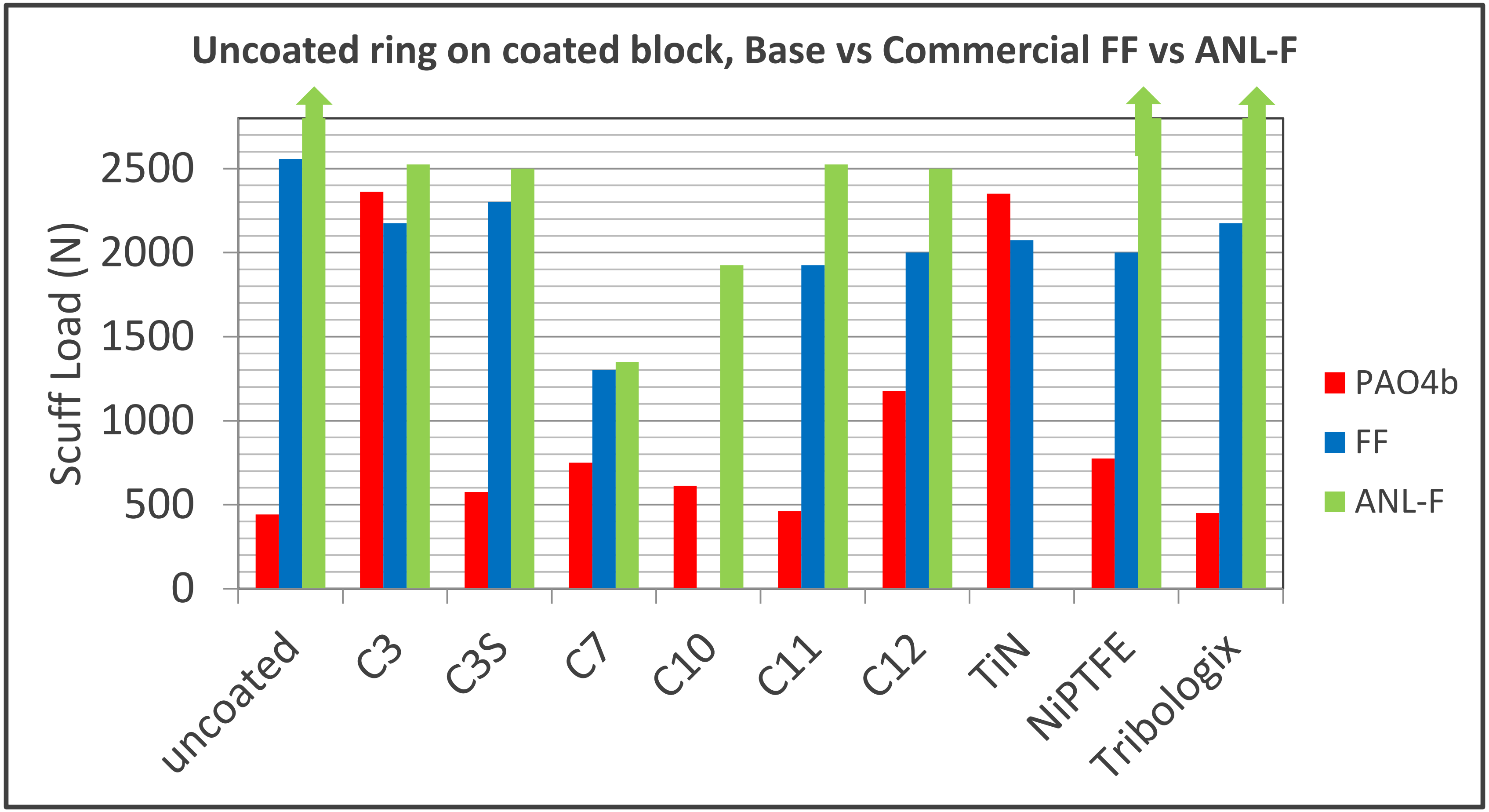
Low viscosity base fluid with appropriate additive system can produce sustained friction reduction and increase scuffing life.

Effect of Lubricant on scuffing Life

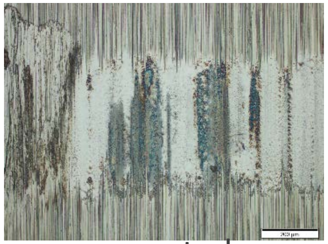


About 2X increase in scuffing life achieved with lubricant technology
- in addition to friction reduction.

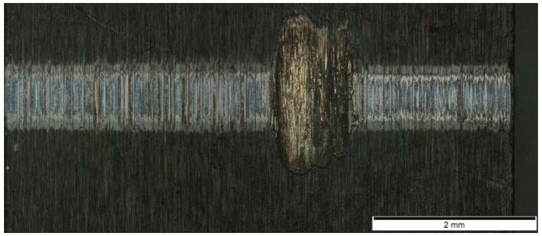
Scuffing performance of coatings and lubricants



With one surface coated, impact of lubricant minimal on scuffing load – Reduced severity of damage



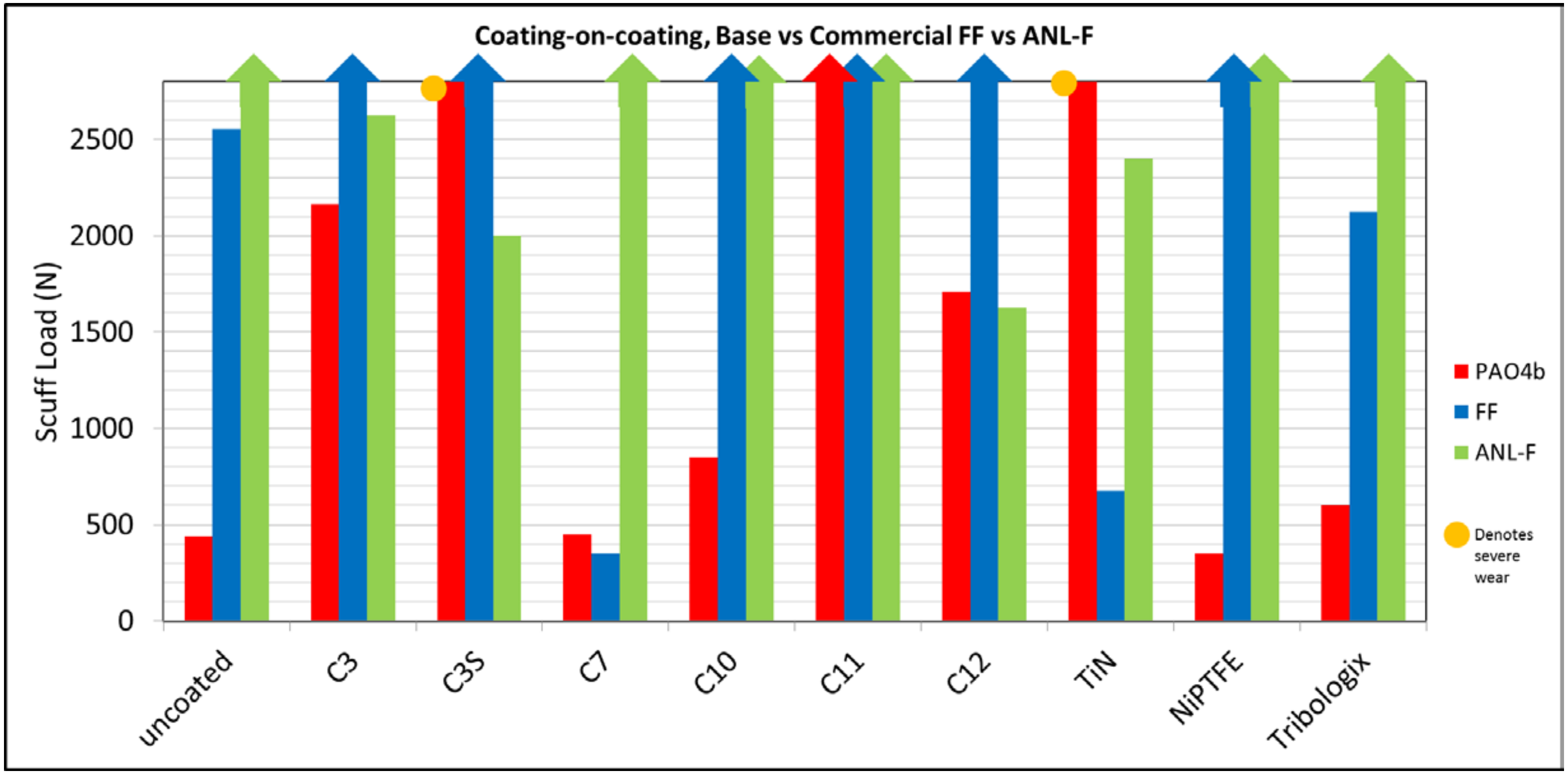
uncoated



C10-Coated

Scuffing performance of coatings

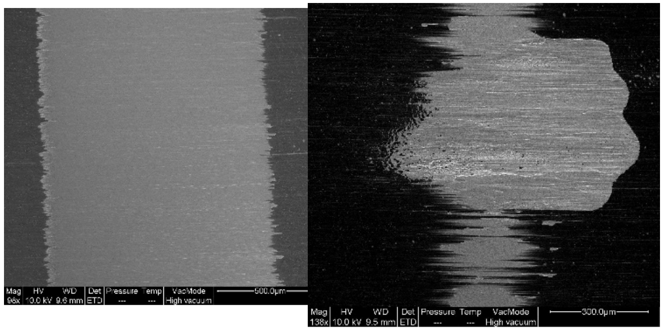
- Synergy between some lubricants and some coatings increased scuffing life

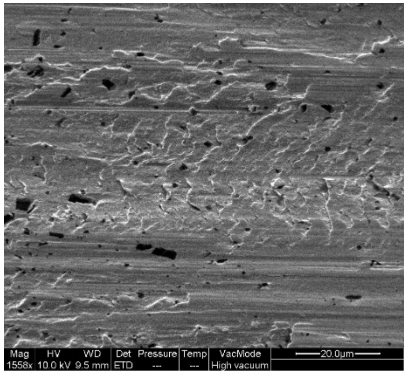


Combined coating and lubricant technologies enabled 2-4 times increase in scuffing life

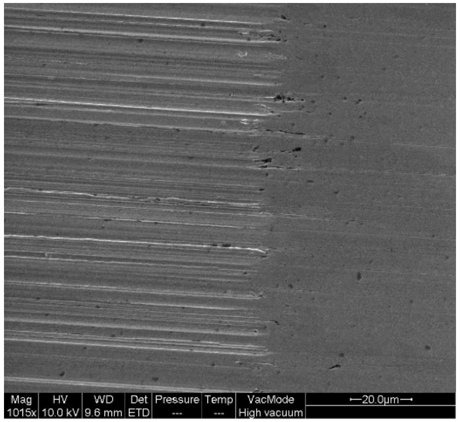
Scuffing Mechanisms in coatings

- In all contact configurations, scuffing occurs only after the coating is worn through.
  - Evidence of shear instability in the substrate
- Coating wear prior to scuffing by different mechanisms - pertinent properties for further scuffing resistance improvement
- In coating and uncoated contact pairs, polishing wear occurs in the uncoated surface
  - Will enhance fluid film lubrication – lower friction, lower wear and better scuffing resistance

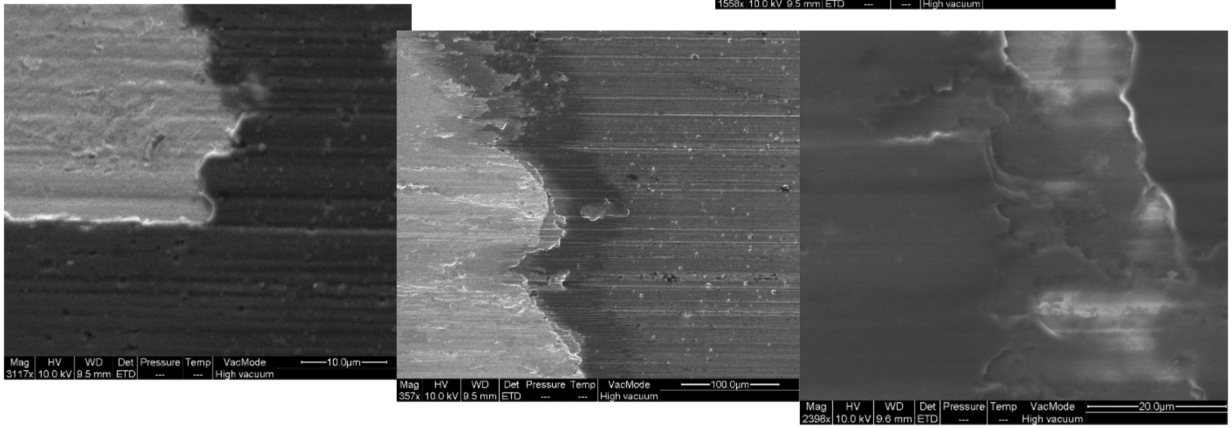




Scuffing after coating removal



Coated ring –uncoated block



Wear mechanisms in coatings

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

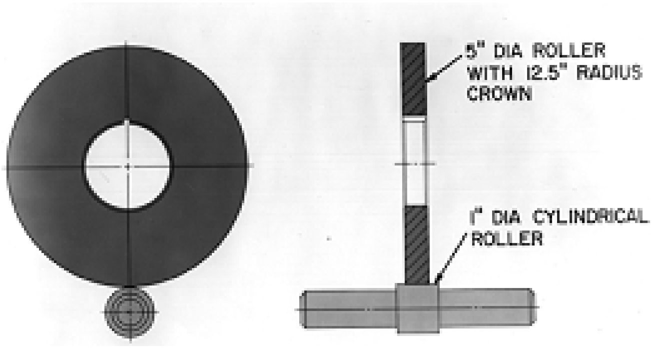
Test parameters:

Stress -- 2.4 - 3.4 GPa

Lambda -- 0.2 - 0.5

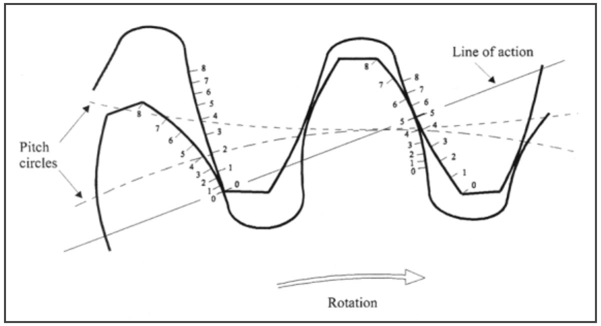
Sliding -- 21%

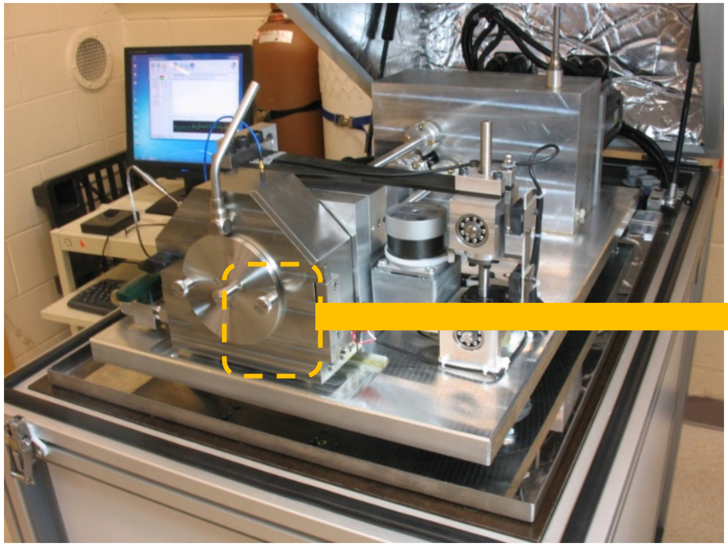
Temperature -- 90 - 105 C

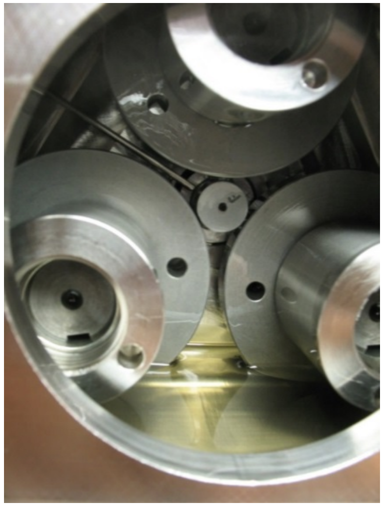


Weibull analysis to determine characteristic pitting life.

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^{o} C

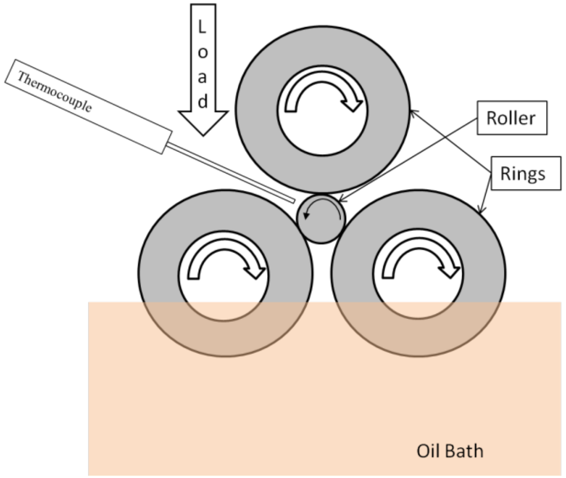
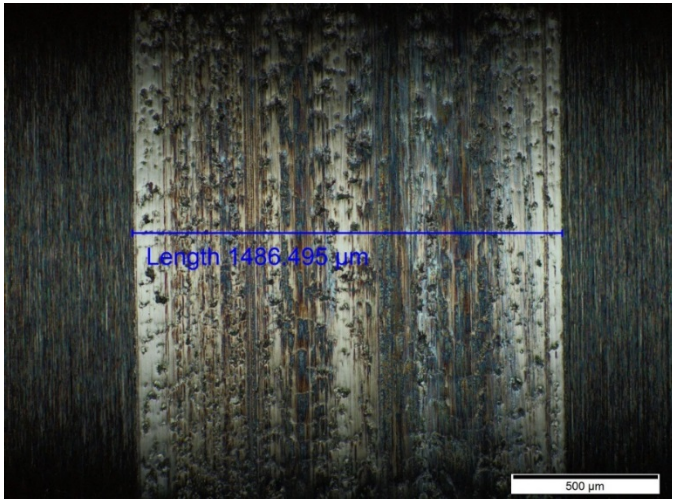


Figure 2: Diagram of MPR layout.

Technical Accomplishment and Progress: *preliminary results*

- 2.84GPa, lambda= 1.7, 80C, 30%SRR, 2.5m/s rolling, 1.6x10^6 Cycles to failure



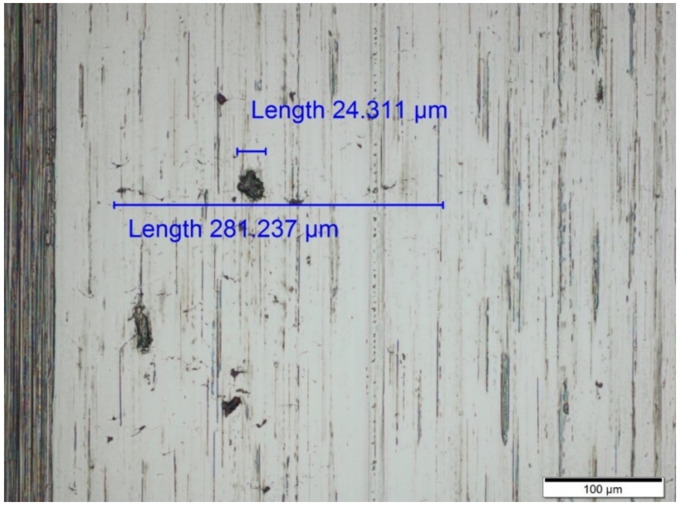
P-P acceleration jumped from ~250 to ~1300 in 100 seconds. Suggests possibility of case crushing

Attempt to accelerate contact fatigue testing resulted in different failure mode

Less severe contact condition - no fatigue propagation

- 2GPa, λ=2, 22%SRR, 1.2m/s, 50° C,
  After 67.6x10^6 Cycles, no fatigue failure
  Increased Wear was negligible
  Slight increase in micro-pitting density
  Defects did not increase in size

  Stopped test after about 80x10^6 cycles (12 days)



More wear prevented fatigue crack propagation

Previous review comments and issues

- All the reviewers agreed the work supports DOE mission but indicated the title is misleading.
  - Response: We fully agree with the need and potential benefit of the work. The title was kept in place for administrative reasons. A subtitle is now added to clarify the focus of the project as the development of enabling technology for high power density gears and bearings.
- Some of the reviewers raised the question of other failure modes not included in the scope of current project – notably bending fatigue and shock failures
  - Response: Indeed, as the severity of contact on meshing gear teeth increases, there will be increase on bending stress which is expected to reduce the bending fatigue life. However, the cleanliness of gear steel alloys is very high now such that bending fatigue failure is extremely rear, even in heavily loaded gears of earth moving equipment. Furthermore, there are technologies such as shot peening and laser shock peening that can be used to effectively increase bending fatigue life. Hence the current project focused on the tribological failure modes, often with contradictory requirements – this is the chief technical barrier to gearbox size reduction.
- One of the reviewers suggested picking a vehicle for study in terms of achievable weight reduction.
  - Response: We feel such an approach may confine the general applicability of the project results to a particular vehicle and perhaps a particular OEM. Doing so may also be making the project a demonstration rather than technology development.

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
  - Many OEM willing to provide guidance, but not formally.
    - Keenly interested in the progress and outcome of work

Remaining Challenges and Barriers

- Assessment of contact fatigue or pitting life for lubricant and coating technologies
  - Time and cost effective and yet valid testing
  - Accelerated testing may change the failure mode
  - Competitive failure modes during testing

- Complexities of lubricant additives with coating surfaces
  - Different types of coatings
    - Additives for ones with adequate wear, scuffing and contact fatigue life

Proposed Future Work

- Continue tribological performance evaluation of coating and lubricant systems.
  - Contact fatigue life evaluation.
  - Mechanism studies of tribochemical interactions between coatings and oil additives.

- In collaboration with lubricant industrial partners, identify and/develop additives that can synergistically work with coatings in terms of wear, scuffing and contact fatigue performance, especially under severe contact conditions.

- Continue continuous dialogue and feed back from pertinent OEM and suppliers.

Summary

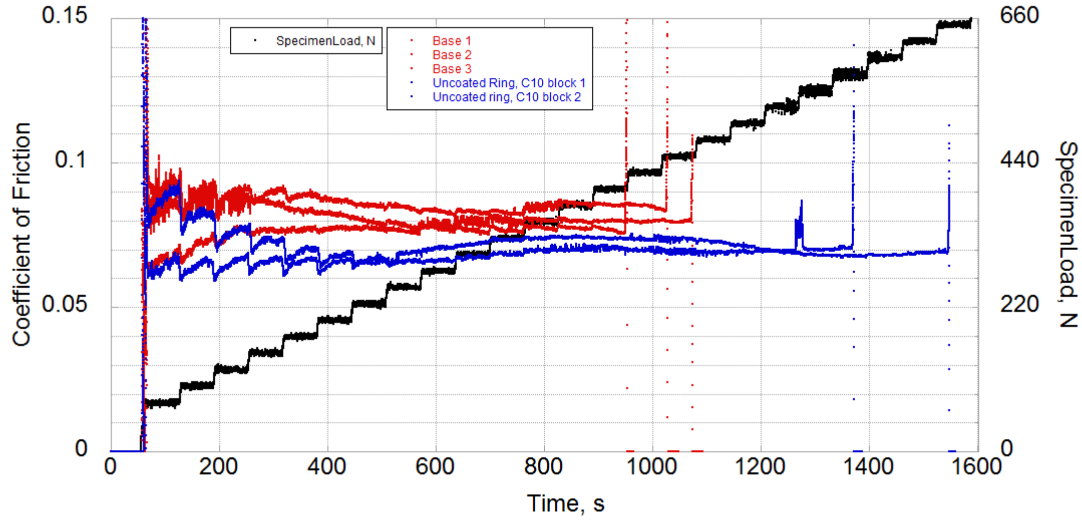
- In order to enable 20% size and weight reduction in high power density driveline system, simultaneous improvement in contradictory failure modes is needed
  - At least 2X increase in wear life.
  - At least 2X increase in scuffing life.
  - At least 3X increase in contact fatigue or pitting life
- With lubricant and coating technologies, demonstrated
  - 4-5X improvement in wear life
  - 2-3X improvement in scuffing life
- Started contact fatigue life evaluation
  - Challenge of test time and proper evaluation of fatigue life with one test rig
  - Limited ability to accelerate the test
    - Too high load can cause case crushing
    - Too low lambda can cause excessive wear and no contact fatigue

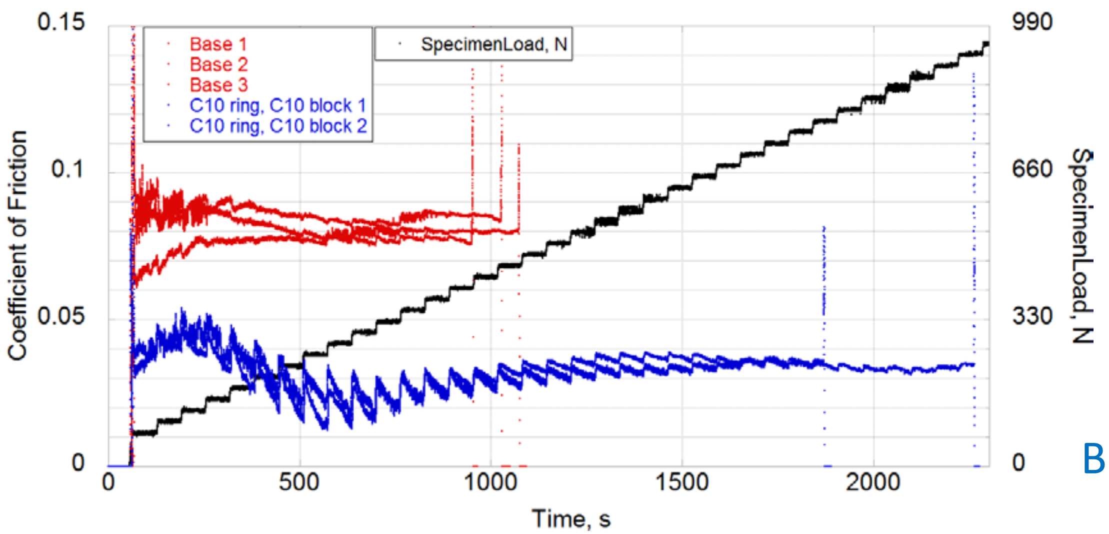
Technical Back-Up Slides

Technical Accomplishment and Progress -Effect of coatings on scuffing

- Coating of one or both surfaces increased scuffing life when tested with low viscosity synthetic base-fluid with no additives

One surface coated

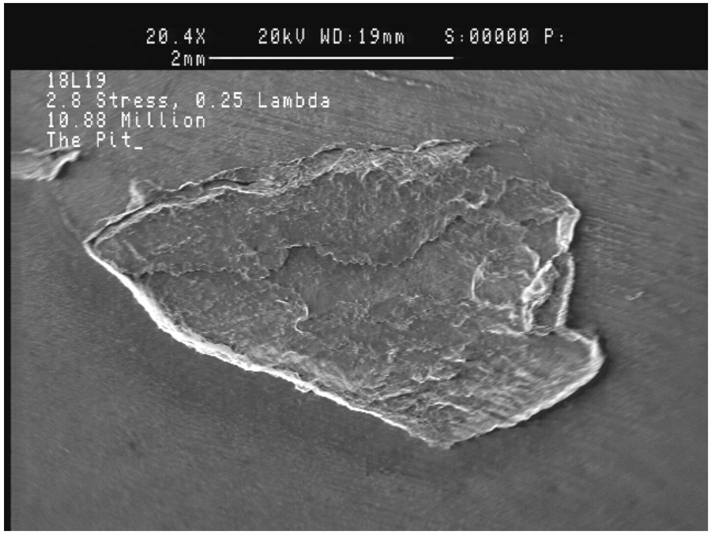


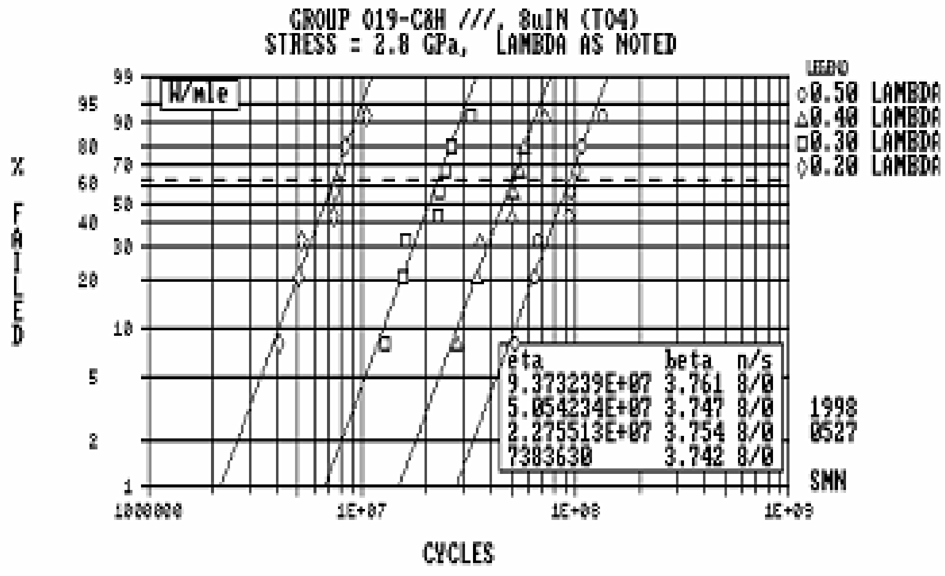


Both surfaces coated

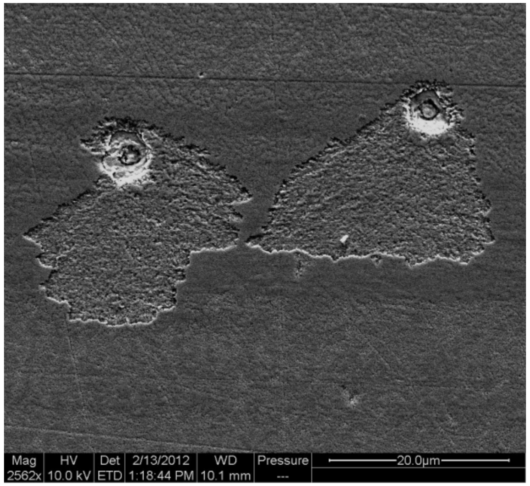
Roller Test Data Analysis and Contact Fatigue Life

Test Roller	Load Roller	Stress (GPA)	Speed (RPM)	Temperature (C)	Initial Lamda	# of Cycles (Millions)
2J19	N34	2.4	3000	106	0.351	58.99
54J19	N24	2.8	2500	105	0.298	64.45
16J19	N15	2.8	3000	111	0.299	39.34
15J19	N20	2.8	3000	99	0.400	49.35
13J19	N361	2.8	3000	99	0.405	(100)R/O
5J19	N31	3.2	2000	104	0.299	34.7
29J19	N19	3.2	2500	108	0.303	43.87
24J19	N22	3.2	3000	99	0.401	64.18
26J19	N25	3.2	3000	99	0.403	2.63
25J19	N23	3.4	3000	106	0.353	1.56



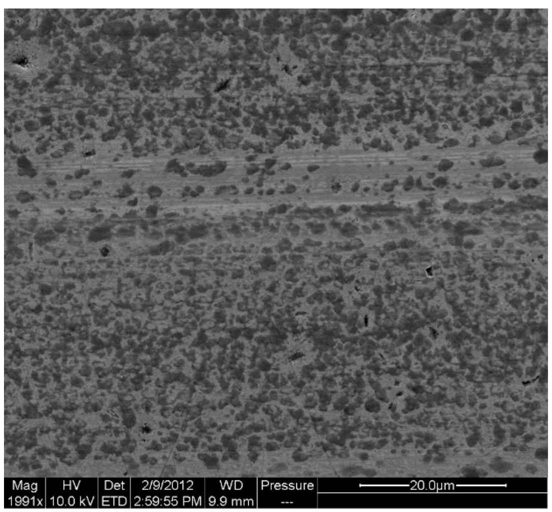


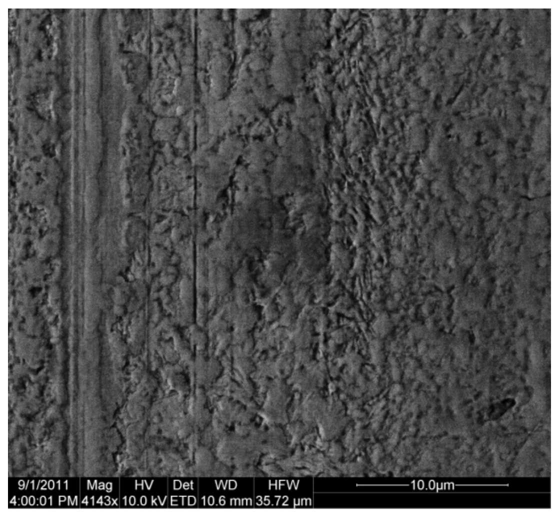
Tribo-Films on coating surfaces

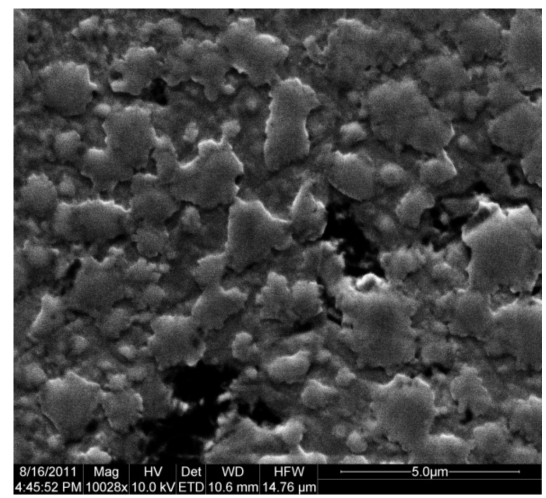


Opportunity to formulate functional additives for coatings

- May enable coating-on-coating contact configuration



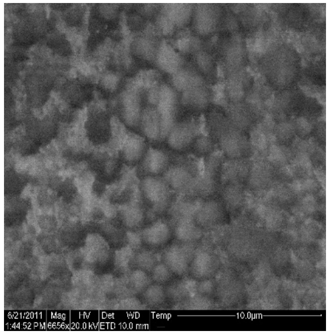




Interaction of coatings and lubricant additives

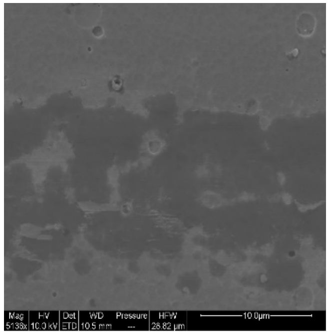
One lubricant and several coatings

Steel



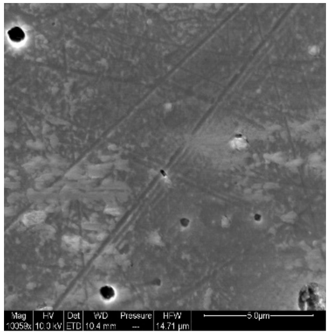
Extensive tribofilm formation

TiN



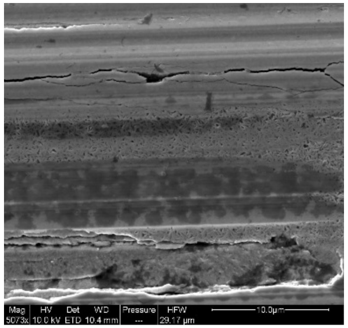
Tribofilm formation

TiCN



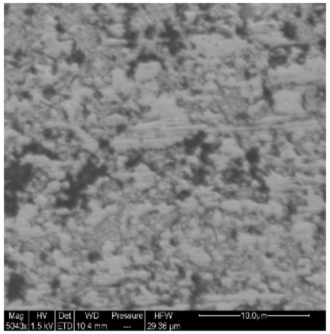
Tribofilm formation and minimal metal transfer

TiB_2



Tribofilm formation and extensive surface damage

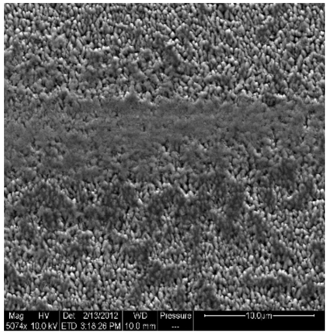
AlTiN



Extensive Metal transfer

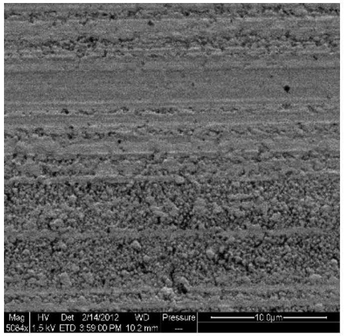
Lubricant: Synthetic A

CrN



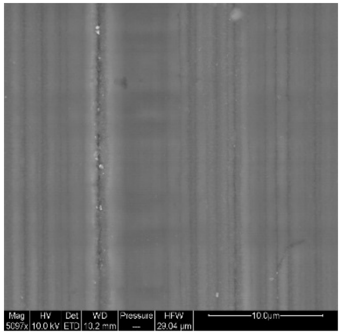
Tribofilm formation

CrSiCN



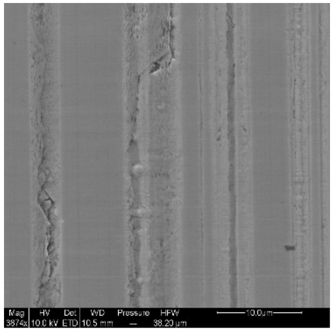
Some tribofilm formation and metal transfer

DLC-1



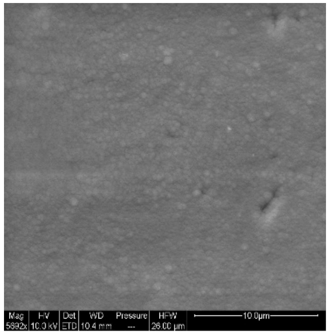
Minimal Interaction- some coating densification

DLC-2



Chemical Interaction- coating damage

DLC-3

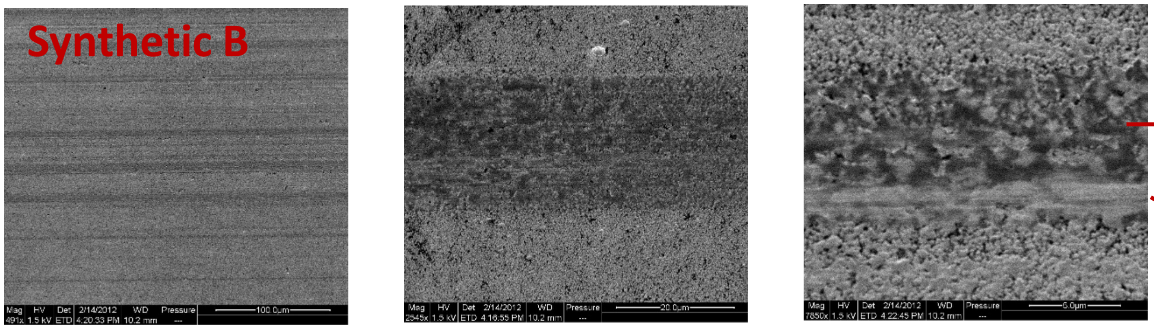


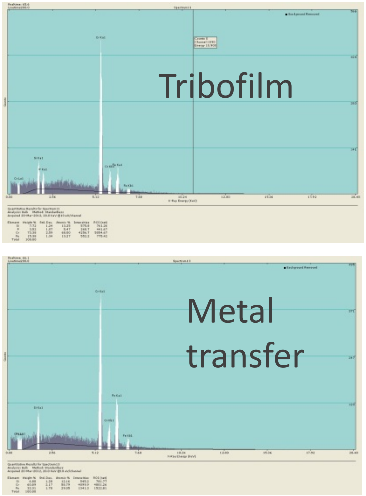
Minimal chemical Interaction and no damage

Interaction of coatings and lubricant additives

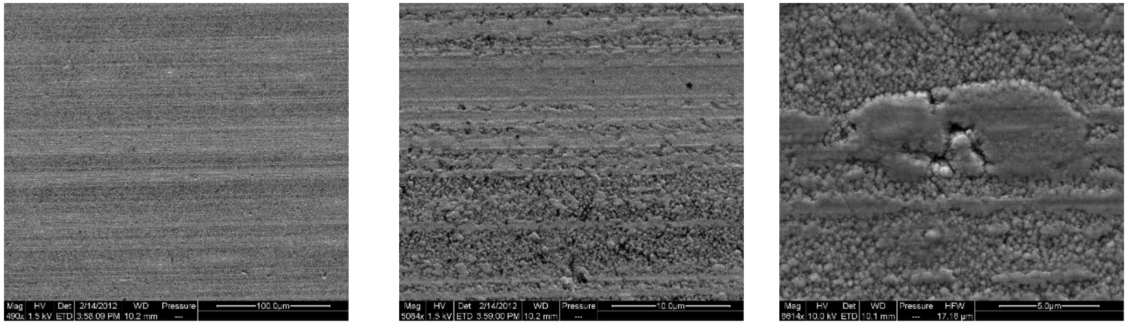
CrSiCN coating with different lubricants

Synthetic B



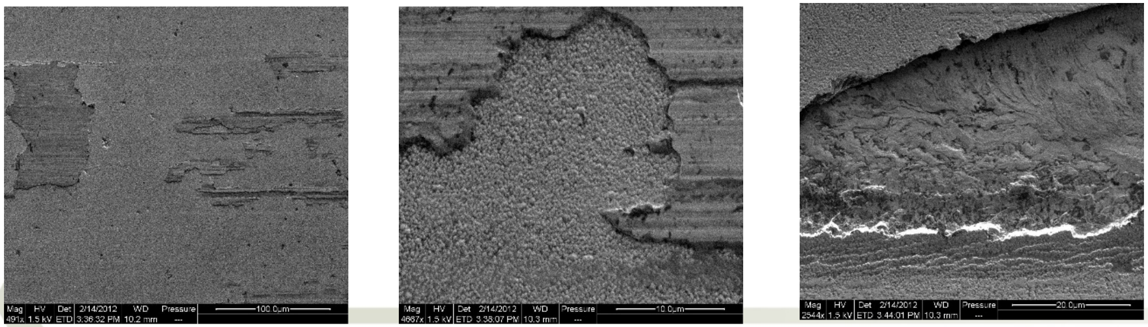


Synthetic A



Some Metal transfer
Tribofilm patches
No surface damage

PAO with no additives



Extensive metal transfer
No tribofilm formation
Surface damage- delamination