Development of High Power Density Driveline for Vehicles

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Project ID # VSS058

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Overview

Timeline

- Start date - October 2010
- End date - FY2015
- Percent complete – 15%

Budget

- Total project funding
  - DOE share – 470K
  - Contractor share – 120K (in-kind)
- Funding
- FY 11 – 170K
- FY12 – 300K

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.
  - Castrol – BP Corp.

Project Description and Relevance

- The main goal of DOE-VTP is the reduction of petroleum use in transportation. Such reduction is accompanied by other benefits.
  - Emissions, economic, environmental, ….
- Significant fuel savings possible through weight reduction in all classes of vehicles.
- Numerous analyses suggests 2 to 5 % reduction in fuel consumption by 10% reduction in vehicle weight
  - An increasingly necessary approach to fuel savings

	NEDC ICEV-G	NEDC ICEV-D
Compact Class	-2.6 %	-3.5 %
Mid-Size Class	-1.9 %	-2.7 %
SUV	-2.4 %	-2.6 %

Calculated Fuel savings in gasoline and diesel vehicles

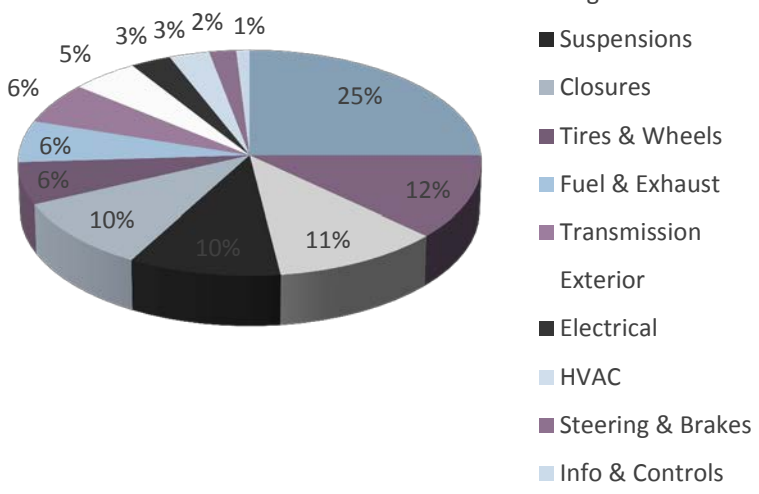
Project Objective and Relevance

- Weight reduction in vehicles must be accomplished without sacrificing safety, reliability and durability

- Based on weight vehicles distribution, systems where significant weight reduction can be achieved are identified.
  - DOE currently have programs for weight reduction in structure and engine – light weight materials

- Driveline system constitutes about 20% of the vehicle's weight
  - Opportunity for weight reduction

Vehicle Weight distribution



Project Objective and Relevance

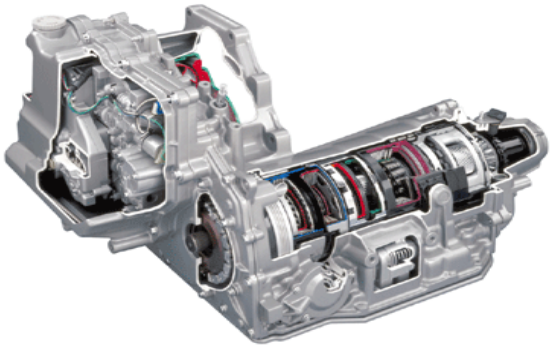
- **Objective:** The ultimate objective of this project is to enable significant vehicle weight reduction through the reduction in size and weight of the driveline systems such as transmission, axle.

- 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

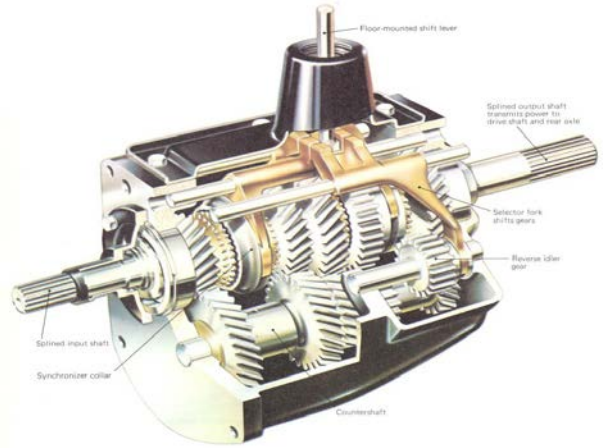
	% Improvement in Fuel Economy / % Weight Reduction EPA Combined (Metro-Highway) Drive Cycle			
	Passenger Vehicle		Truck	
	Base Engine	Downsized Engine	Base Engine	Downsized Engine
Gasoline	0.33%	0.65%	0.35%	0.47%
Diesel	0.39%	0.63%	0.36%	0.46%

Technical Approach/Goals

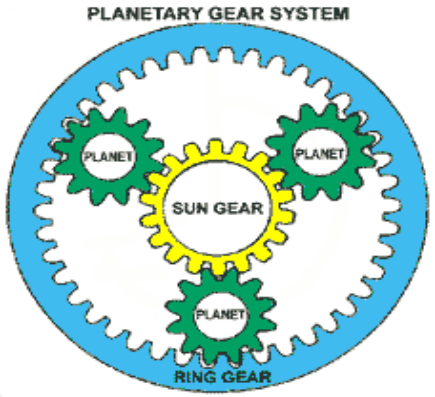
- Vehicle driveline systems – transmission, axles consist of planetary gear systems and bearings.



- In order to reduce the size of the planetary gear system, high power density gearing and bearings will be required.
  - High severity of contact in gears and bearing
  - Reliability and durability issues
    - Wear; scuffing; and contact fatigue (pitting)



Goal: Develop and evaluate integrated materials, surface and lubricant technologies needed to enable HPD driveline



Technical Approach

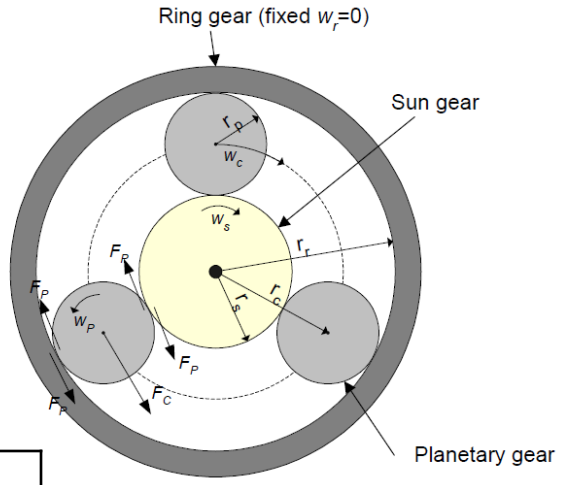
- In order to establish materials, surface and lubricant technologies target and goals , analyses must be conducted to
  - Determine gear contact kinematics for gearbox with different levels of size reduction in a planetary gear system
  - Determine impact of new contact parameters on gearbox reliability 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

FY 11: Accomplishments

- Conducted gear kinematics analysis to determine impact of size reduction on contact stresses, surface velocities in planetary gear system
- Effect on gear reliability and durability evaluated
  - Scuffing, wear and contact fatigue life reduction



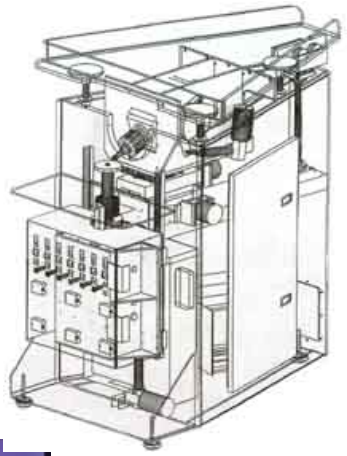
Size reduction (%)	Scuffing life reduction (%)	Contact fatigue life reduction (%)	Wear life reduction (%)
5	5.2	28.9	5.2
10	11.1	50.4	11.1
15	17.6	66.1	17.6
20	25.0	77.4	25.0
25	33.3	85.3	33.3
30	42.9	90.7	42.9
35	53.8	94.3	53.8
40	66.7	96.7	66.7
45	81.8	98.1	81.8
50	100	99.0	100

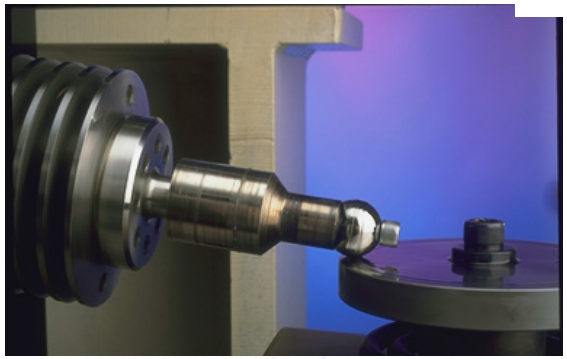
FY 12 Accomplishment: Test methodology for gear Contact

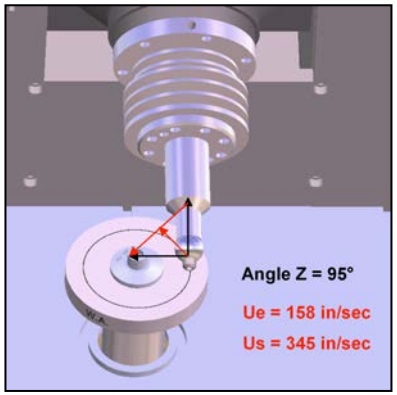
Independent control of surface velocities allows evaluation of tribological phenomena at meshing gear teeth.

- Frictional behavior
- Failure and damage mechanisms

1. Contact configuration: Ball vs. Disk
2. Contact stress: 2.1 to 2.2 GPa
3. Temperature: 75 ^{0}C
4. Percent Sliding: 40%

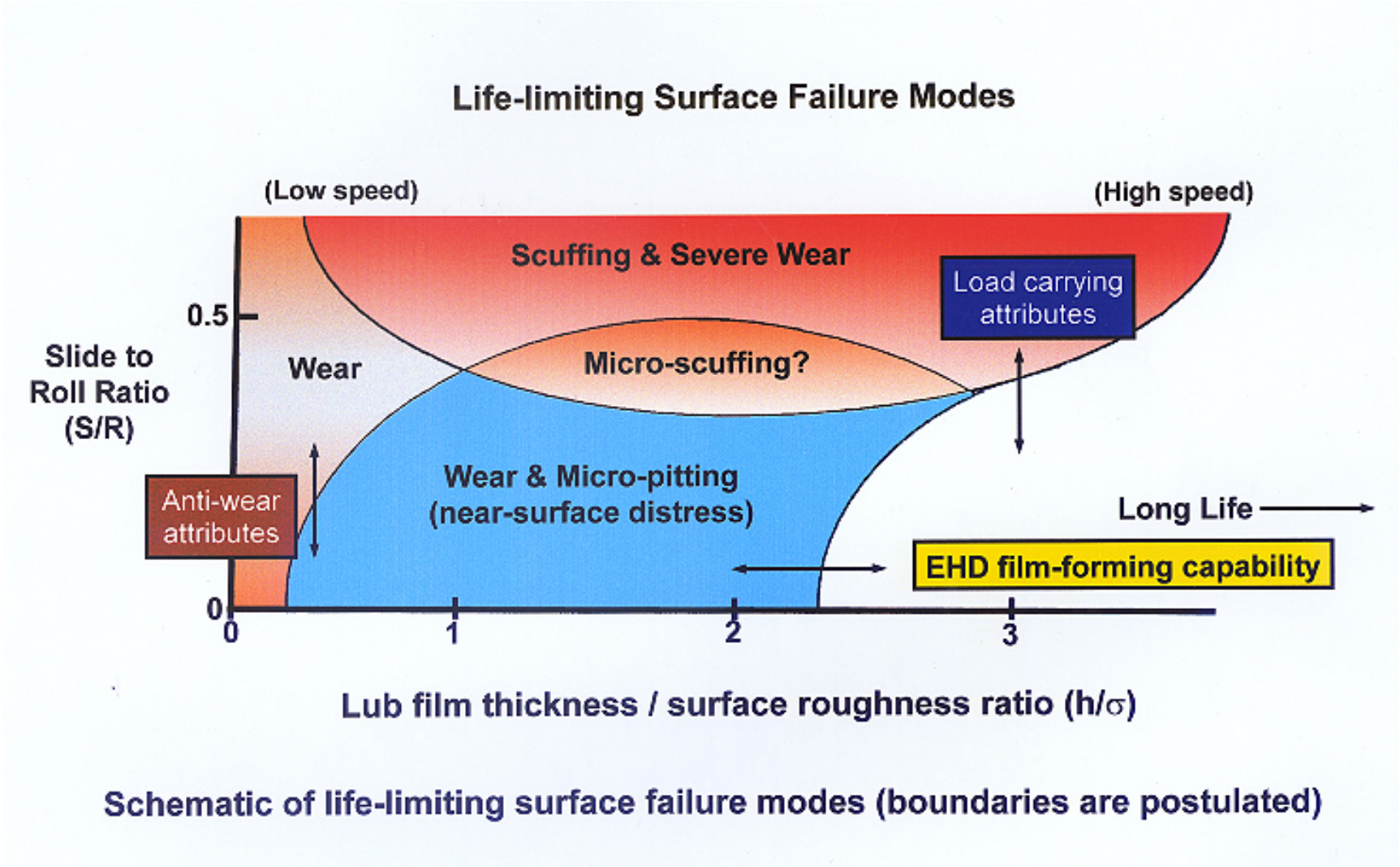






Wedeven Associates, Inc.
5072 West Chester Pike
Edgmont, PA 19028-0646
(215) 356-7161

FY 12 Accomplishment: Test methodology for gear Contact



Schematic of life-limiting surface failure modes (boundaries are postulated)

FY 12 Accomplishment: Wear Life Improvement

- Thin-film tribological coatings and lubricant formulation with anti-wear additives are two technologies commonly used for wear life improvement
  - Integration of both can be a viable pathway to achieve wear life requirement for HPD gearbox
- Evaluated friction and wear performance of coatings and lubricants

Coatings	Deposition method	Type	Thickness (µm)	Manufacture Hardness (Hv)	Nano Hardness (GPa)	Roughness (nm)
4118-Steel	none	No layer	0	850	7	19
DLC-1	PACVD	multilayer	1.9	1200-1500	12-15	172
DLC-2	PACVD	multilayer	2.6	1000-1500	10-15	133
DLC-3	PACVD	multilayer	3.5	1500-3000	16	56
CrN	PVD	monolayer	5.0	800-1100	10	16
CrSiCN	PVD	monolayer	3.4	2700-3000	29	6.6
AlTiN	PVD	bilayer	2.4	3500	34.5	91
TiB_2	PVD	monolayer	1.9	3650	34-37	30
TiCN	PVD	monolayer	0.9	4000	39	49
TiN	PVD	monolayer	3.7	3000	29-30	87

Coatings Evaluated

LUBRICANT	PAO-10	PAO-4+ Additives	Synthetic A	Synthetic B
Viscosity 40°C (cSt)	71.1	15-20	233.5	132
Viscosity 100°C (cSt)	10.70	4.20	18.7	17.5
Viscosity Index	-	-	92	146
Flash point (°C)	272	204	235	221
Pour point (°C)	-51	-57	-15, 5	-45
Density (kg/m^3) at 15.6C	837	819	905	860

Lubricants

- **PAO10**: synthetic basestock (no additives)
- **PAO4+Additives**: synthetic basestock + 2.5wt. % ZDDP+ 2.5 wt. % MoDTC
- **Synthetic A**: optimized for friction control
- **Synthetic B**: optimized for wear protection

Lubricants Evaluated

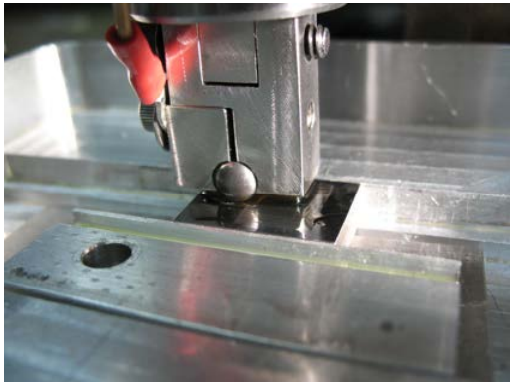
FY 12 Accomplishment: Wear Life Improvement

Friction and wear testing for coating and lubricants

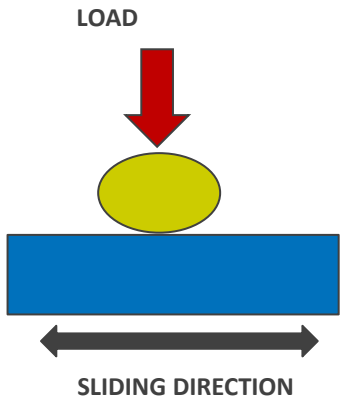
- Reciprocating sliding contact roller-on-flat configuration
- Friction continuously monitored.

Test Parameters

- Load: 150N σmean=0.33 Gpa.
  σmax=0.42 Gpa.
- Speed: 0.5 Hz (ave. speed: 1cm /s)
- Stroke length: 10 mm
- Duration: 180 minutes
- Temperature: 100°C



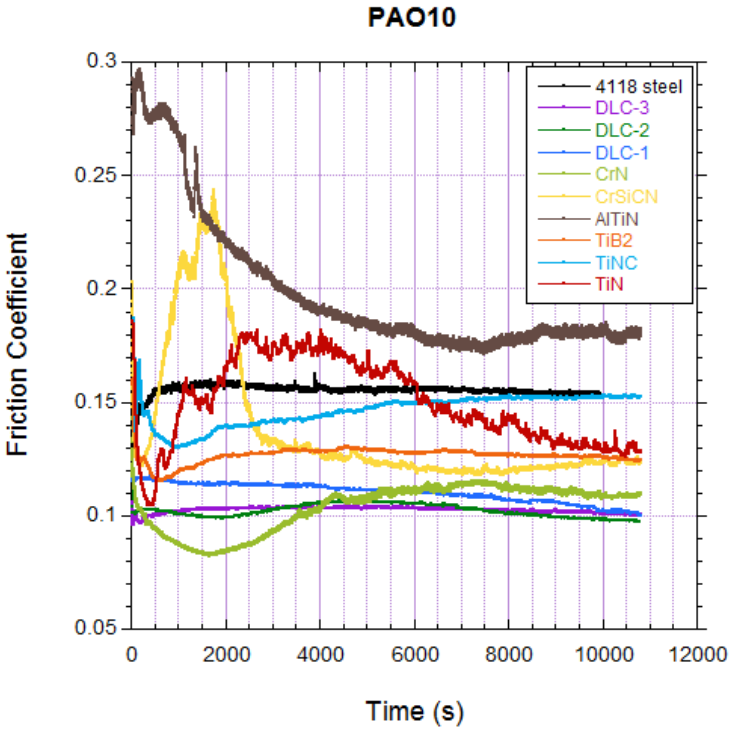
Roller-on-flat Configuration

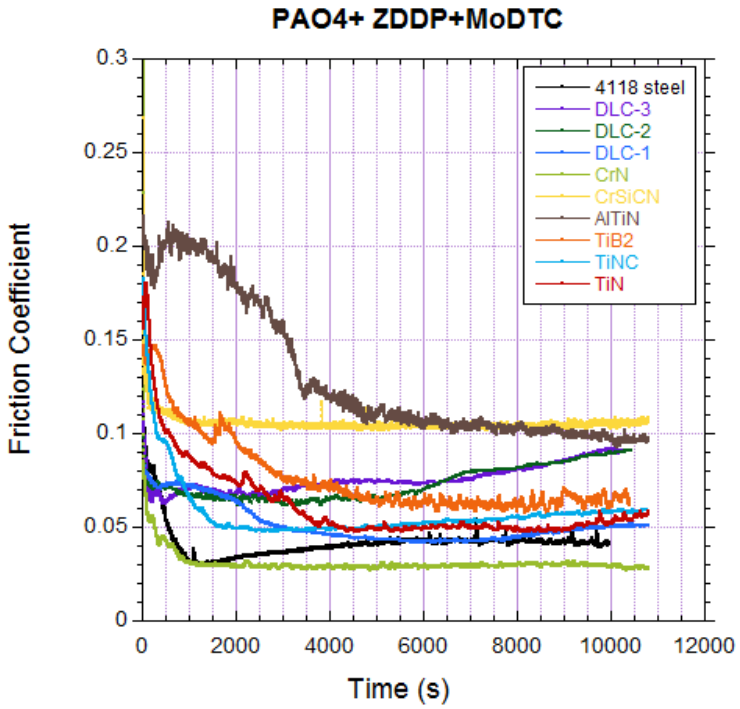


FY 12 Accomplishment: Wear Life Improvement

Friction Results for tests with model lubricants

- In unformulated basestock lubricant, some coatings reduced friction
- In oils with additives, friction was higher for almost all the coatings

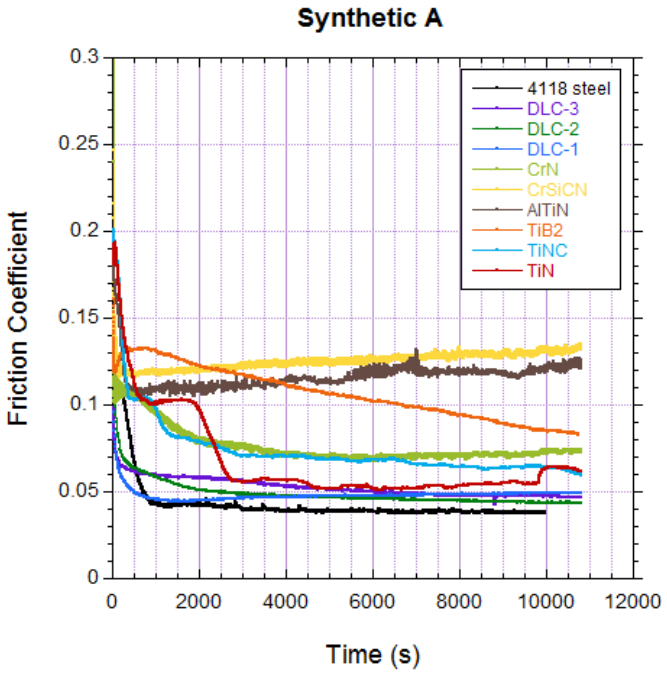


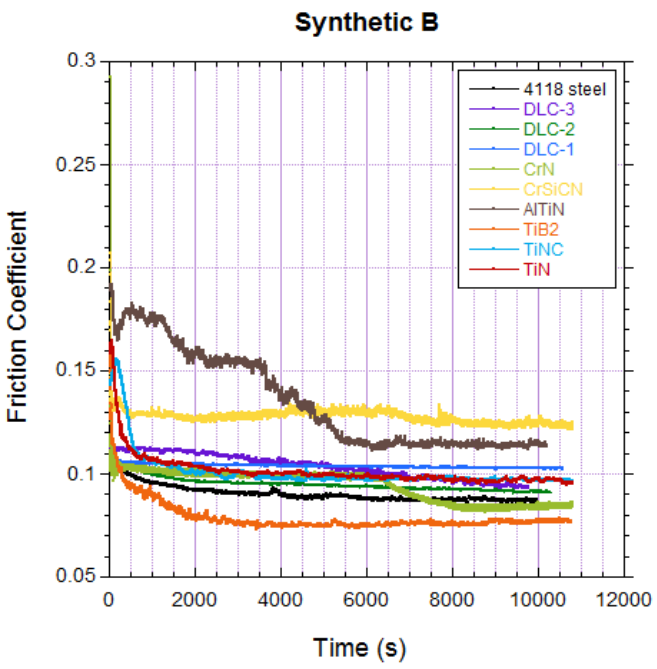


FY 12 Accomplishment: Wear Life Improvement

Friction Results for tests with fully formulated lubricants

- In fully formulated lubricants, friction is higher in tests with the coatings
- Different levels of tribochemical interaction between coatings and oil additives



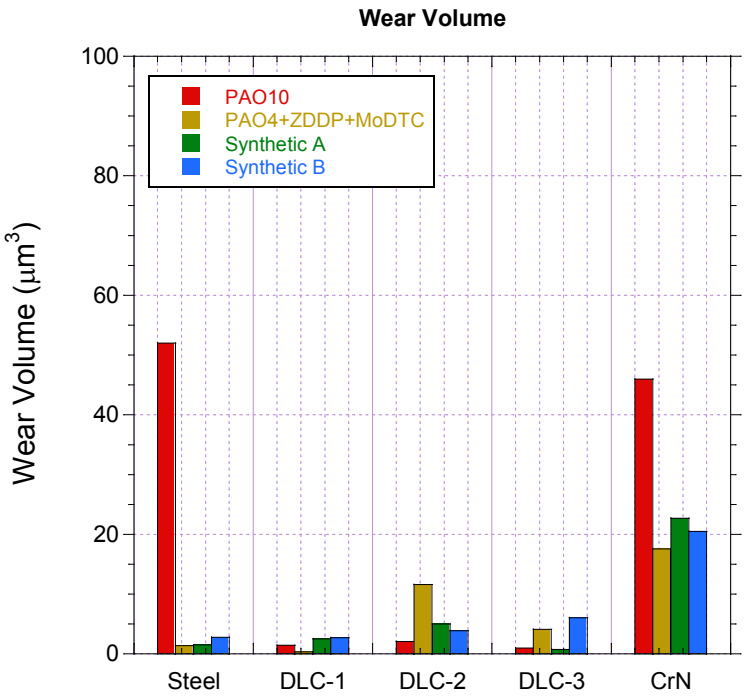


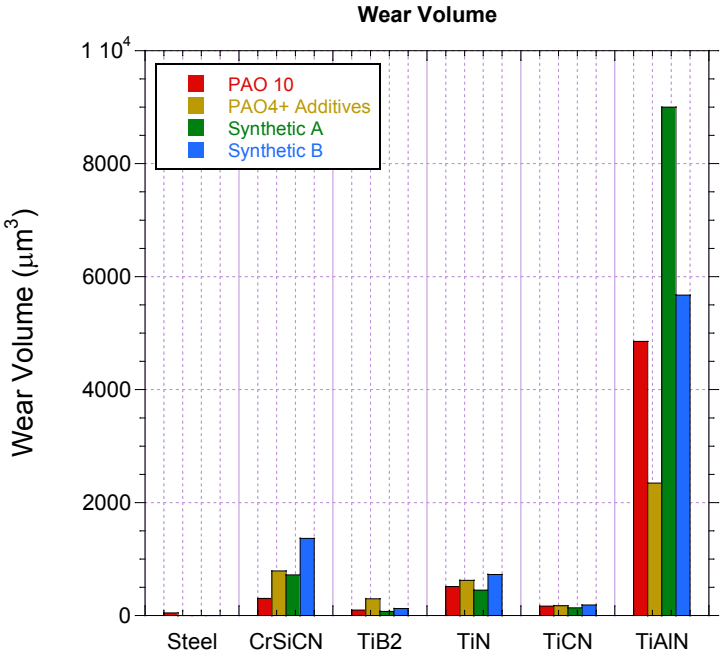
Coatings reduced the effectiveness of oil additives in terms of friction

FY 12 Accomplishment: Wear Life Improvement

Wear Results for tests with different lubricants and coatings

- Minimal wear observed on the flat specimens
- Wear measured on the roller specimen



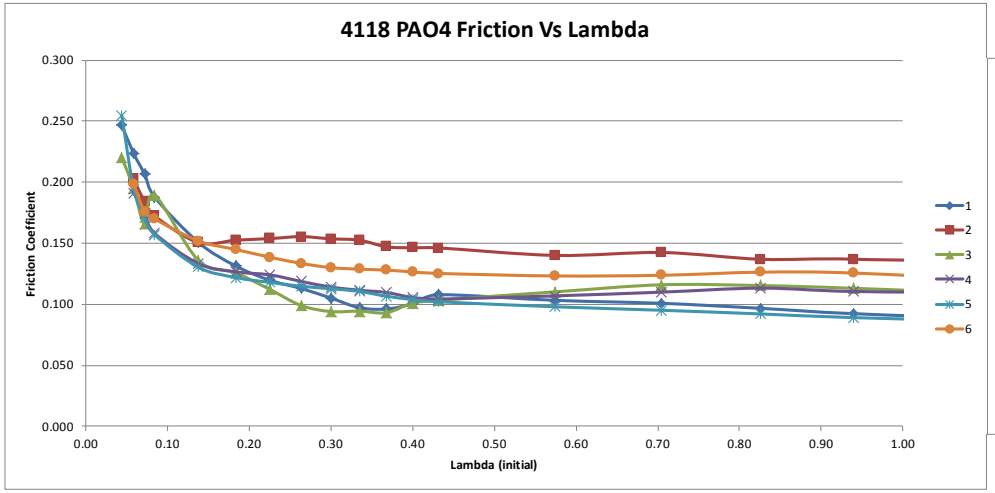


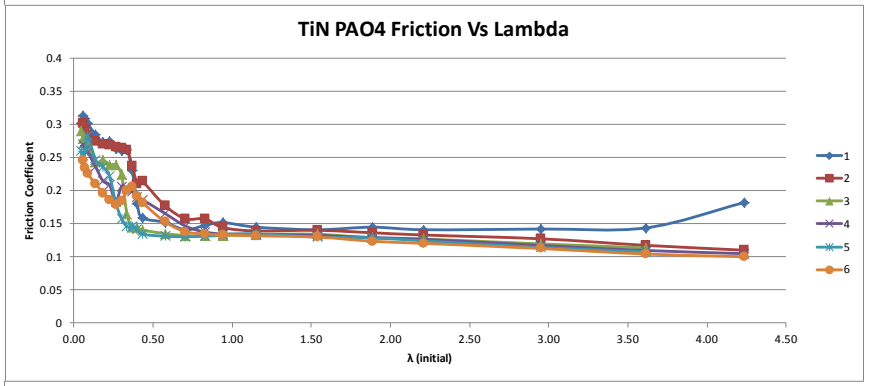
Note the difference in scale of the two Figures

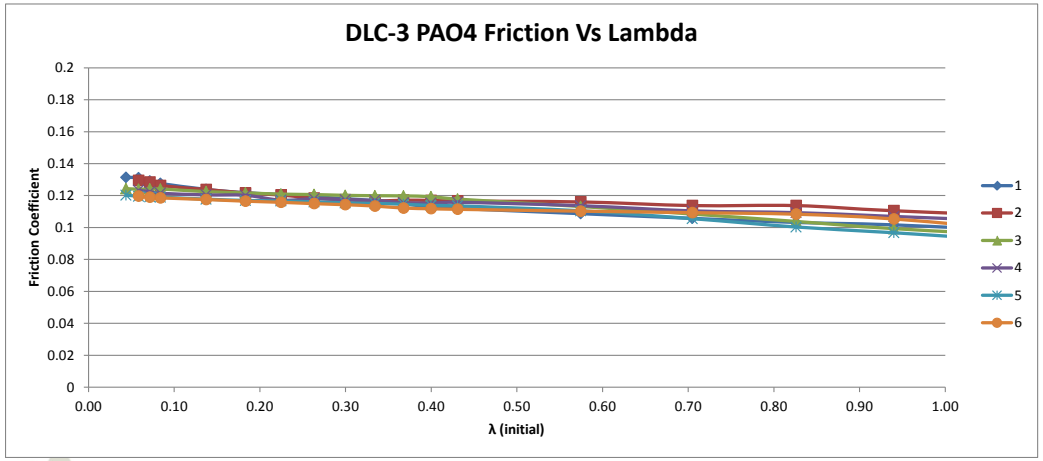
Coatings must be selected wisely for wear life improvement in gears

FY 12 Accomplishment: Effect of coatings on lubrication regime transition

- Transition in lubrication regime was assessed by a step speed increase protocol in unidirectional sliding







Some coatings are beneficial for fluid film lubrication, others are not. Opportunity for integration of coating and lubricant technologies for optimal tribological performance

Collaborations

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

- **Afton Chemical Corp. (industry):**
  - Development of lubricant additives for coatings to ensure adequate wear, scuffing and contact fatigue life
  - (Possible CRADA talk between ANL and Afton in progress).

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

Proposed Future Work

- Continue tribological performance evaluation of coating and lubricant systems with appropriate test methodologies.
  - Wear, Scuffing and Contact fatigue life.
  - Mechanism studies of tribochemical interactions between coatings and oil additives.

- In collaboration with industrial partner (WAI), identify and evaluate material attributes and technologies for HPD gearing.

- 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

Summary

- Significant weight reduction and consequent fuel savings and emissions reduction can be achieved in all transportation vehicle platforms by reducing the size and weight of the driveline system.
  - Can enable downsizing of powertrain system, resulting in more fuel savings.

- In order to reduce the size and weight of driveline systems without loss of transmitted power, high power density gearbox will be required.
  - Analyses showed the need to significantly increase the wear, scuffing and contact fatigue life

- Appropriate test methodology was developed to adequately evaluate performance of candidate technologies under gear contact kinematics.

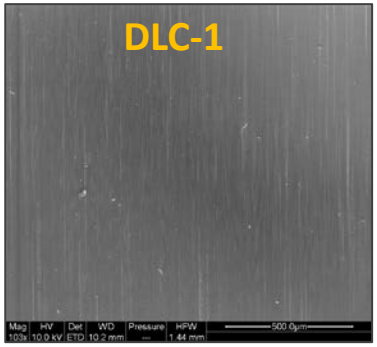
- Initial performance evaluation of thin-film coatings and lubricant additives show promise to simultaneously increase in wear, scuffing and contact fatigue life.

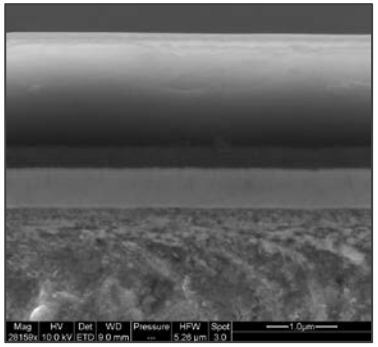
- Integrated materials, surface and lubricant technologies will be needed to enable the development of a reliable and durable high power density driveline systems for transportation vehicles.

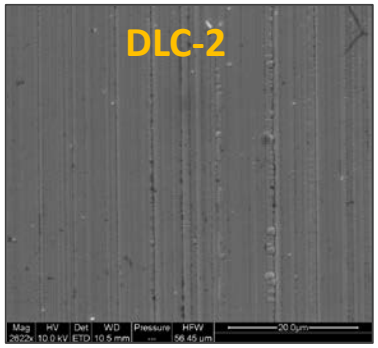
Supplemental Slides

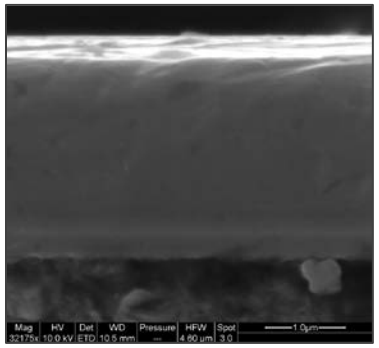
- Provides some information on the structure of coatings evaluated and assessment of tribochemical interaction between coatings and lubricant additives.

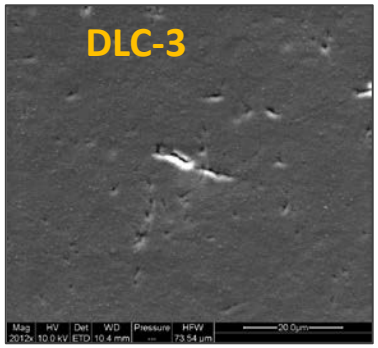
Some coatings cross-sections

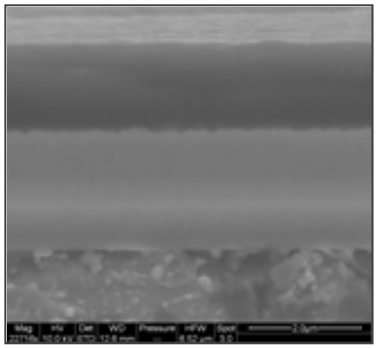


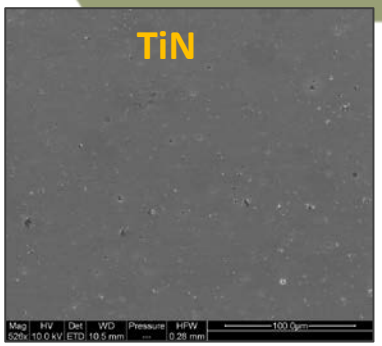


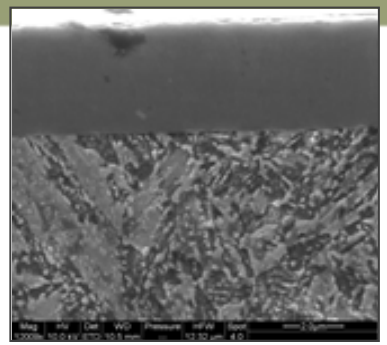


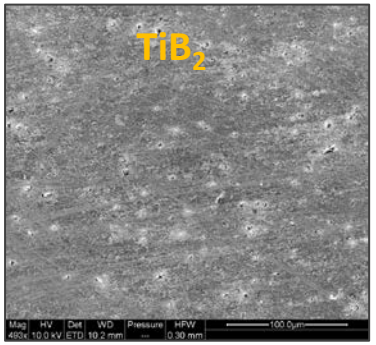


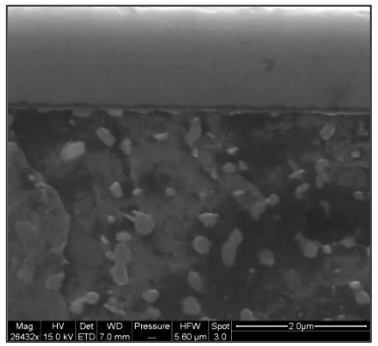


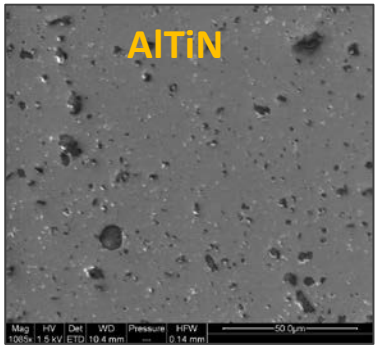


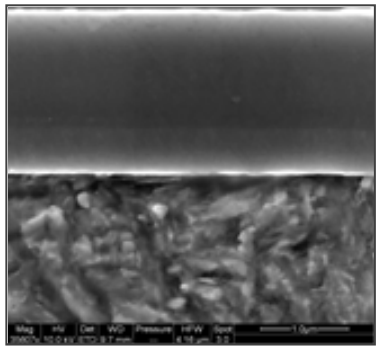


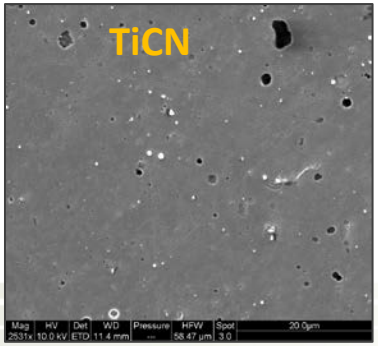


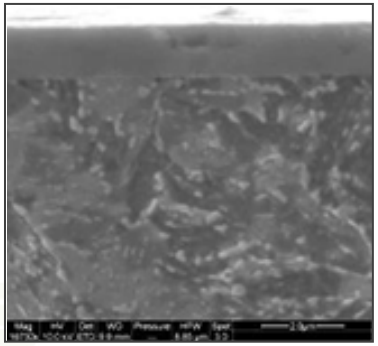








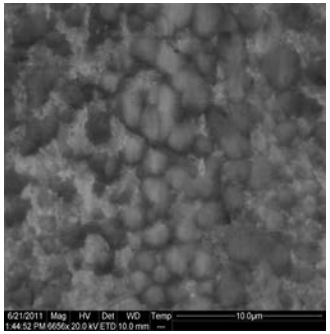




Interaction of coatings and lubricant additives

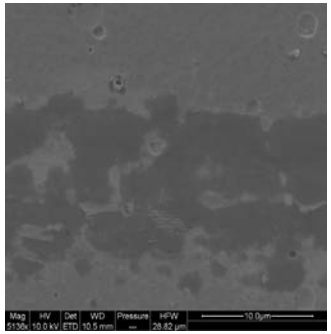
One lubricant and several coatings

Steel



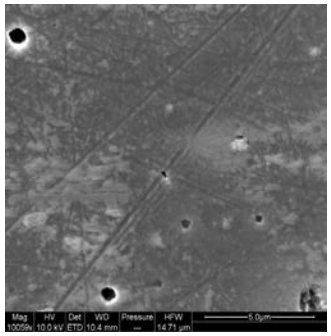
Extensive tribofilm formation

TiN



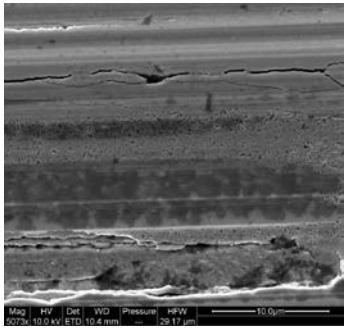
Tribofilm formation

TiCN



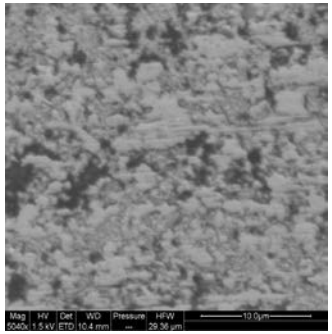
Tribofilm formation and minimal metal transfer

TiB_2



Tribofilm formation and extensive surface damage

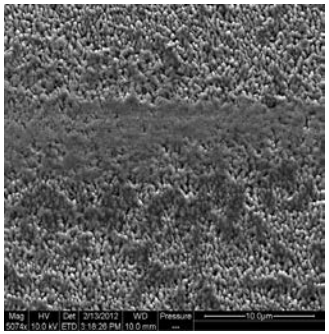
AlTiN



Extensive Metal transfer

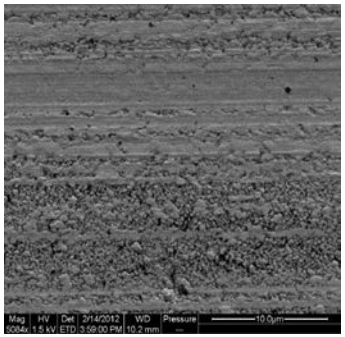
Lubricant: Synthetic A

CrN



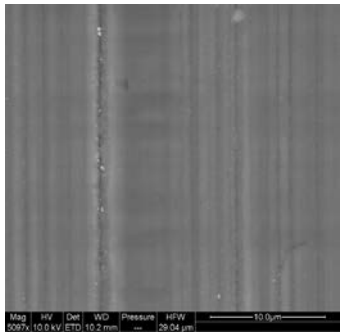
Tribofilm formation

CrSiCN



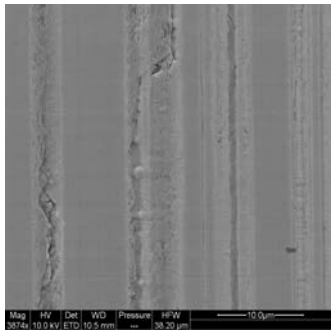
Some tribofilm formation and metal transfer

DLC-1



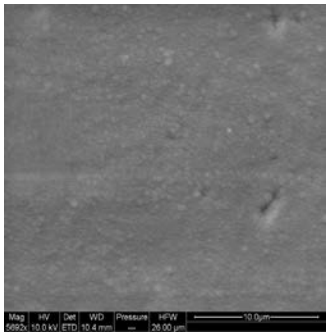
Minimal Interaction- some coating densification

DLC-2



Chemical Interaction- coating damage

DLC-3

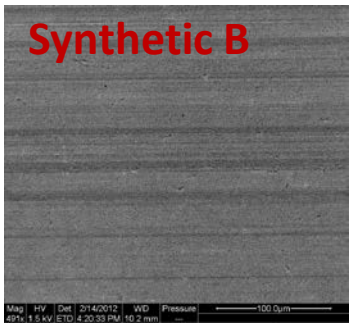


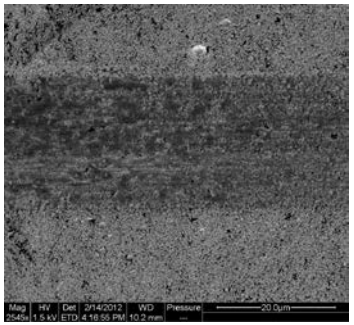
Minimal chemical Interaction and no damage

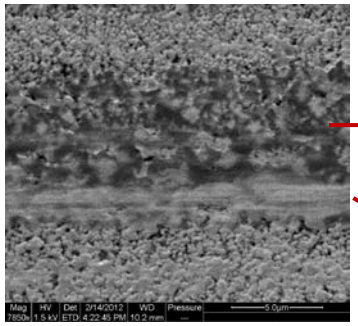
Interaction of coatings and lubricant additives

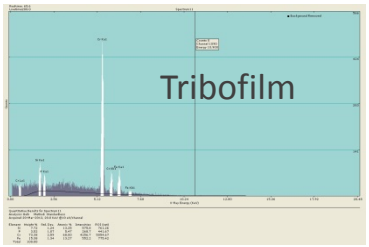
CrSiCN coating with different lubricants

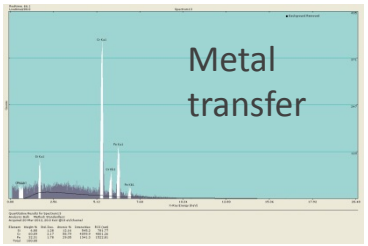
Synthetic B



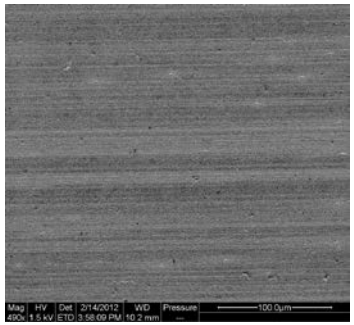


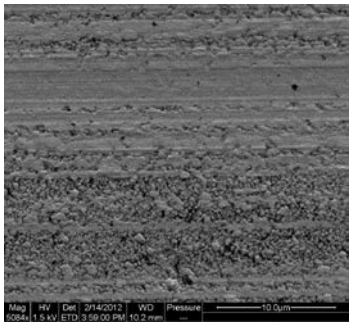


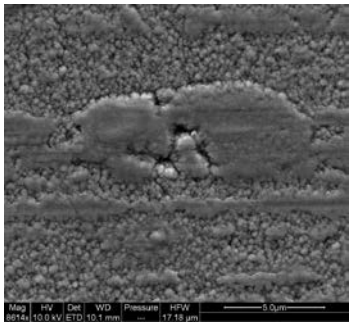




Synthetic A

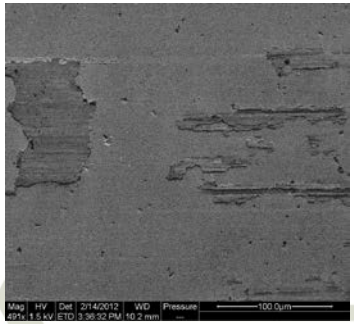


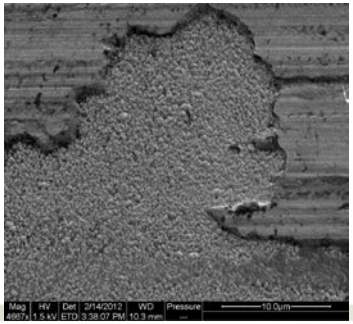


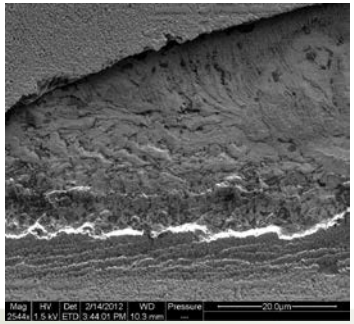


Some Metal transfer
Tribofilm patches
No surface damage

PAO with no additives





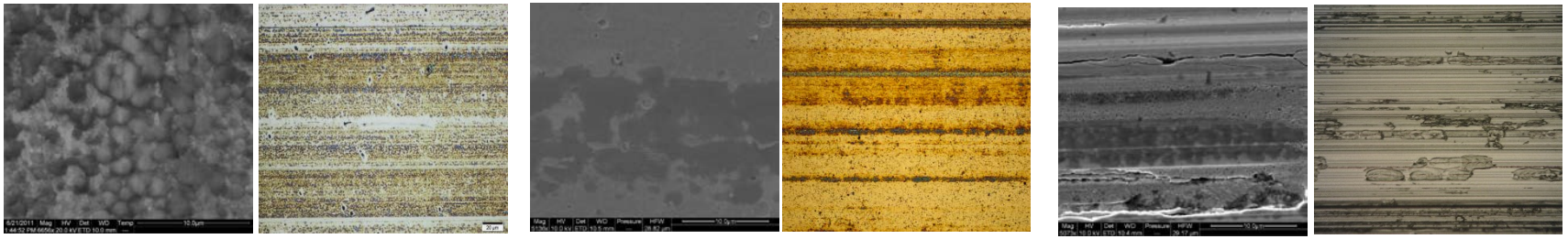


Extensive metal transfer
No tribofilm formation
Surface damage- delamination

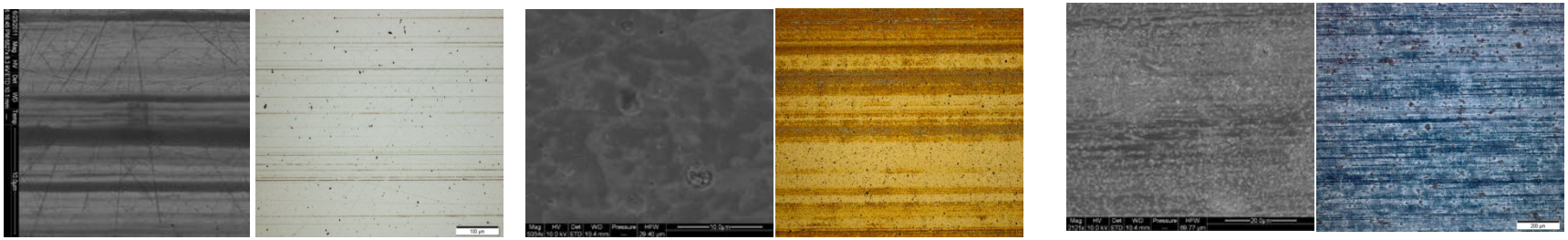
Interaction of coatings and lubricant additives

Several lubricants and several coatings

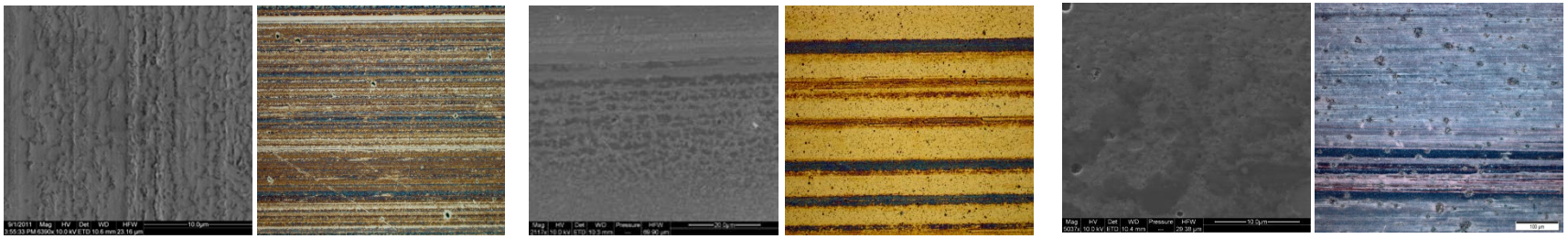
Lubricant: Synthetic A



Lubricant: Synthetic B



Lubricant: PAO4+ZDDP+MoDTC



Steel TiN TiB_2