Advancements in development of energy-saving lubricants and coatings for automotive applications

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Part I:

Lubrication engineer's outlook on tribology

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Lubrication engineer's outlook on tribology

"*Tribology is the science and practice of interacting surfaces in relative motion and of the practices related thereto*"

Peter Jost (1966)

A broad scope of problems

cardiovascular, orthopaedic and dental implants ... as well as real synovial joints

from micro ...

to macro size

various mechanical appliances

Bridging the gap

Dietician:
Studies different dishes trying to explains what is good and what isn't.

Chef:
Selects right ingredients and cooks something edible for acceptable price.

Researching into friction and wear

Friction is bad	Friction is good
Energy losses in engines Chatter, squeaking Undoing a tight screw	Tire and shoe sole grip Playing violin Screw coupling

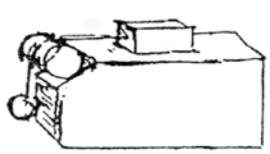
Wear is bad	Wear is good
Machines and tools Artificial joints Tires	Grinding Polishing Worn-in jeans manufacture

Tribologists are friction researchers, no objection.

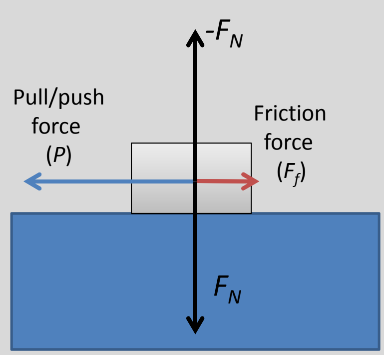
Who are lubrication engineers then? Friction fighters?

No, rather friction masters!

Coefficient of friction



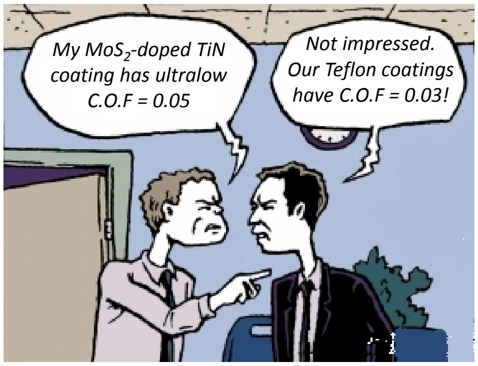
Leonardo Da Vinci
(1452-1519)



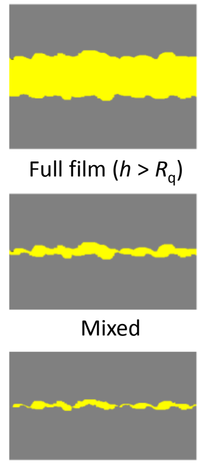
$F_f = \mu F_N$

The heavier subject, the more difficult to pull it.

Why coefficient of friction is fiction

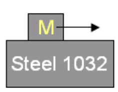


A totally futile debate! Depending on system configuration and measurement conditions, coefficient of friction can be anywhere from 0 to infinity.



Tribosystem

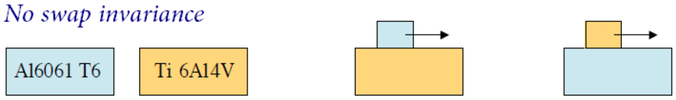
Depends on probe material



air

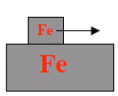
M:	
Al6061 T6	$\mu = 0.38$
Copper	$\mu = 0.25$
Steel 1032	$\mu = 0.23$
Teflon	$\mu = 0.07$

No swap invariance



$\mu = 0.38$ $\mu = 0.29$

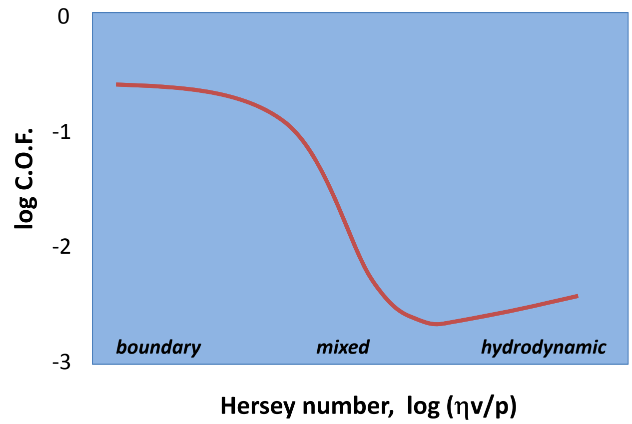
Depends on environment



Vacuum	$\mu > 4$ (seizure)
10^{-3} bar O_2	$\mu = 1.5$
1 mbar O_2	$\mu = 0.4$
Oil film	$\mu < 0.1$

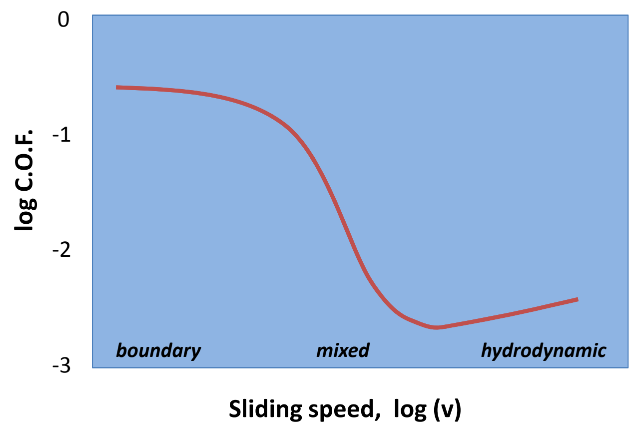
- Coefficient of friction is a characteristic of tribosystem and not of individual material.
- Real surfaces are never absolutely clean and absolutely smooth.

Stribeck diagram



The Stribeck diagram is difficult to measure rigorously because p is ill-defined.

pseudo-Stribeck diagram



- *Effects of wear are mixed in. Result depends upon normal force.*
- *Contact pressure decreases in the course of measurement.*
- *Low-speed to high-speed and high-speed to low-speed curves do not coincide.*

Types of lubricants

Type	Applications
Lube oils	Automotive lubricants, industrial gear oils, hydraulic fluids, etc.
Oil in water emulsions	Cutting fluids, rolling emulsions, fire-resistant hydraulic fluids
Water in oil emulsions	Metal forming
Greases	Bearings, slideways
Solid lubricant suspensions, e.g. graphite	Forging and extrusion applications
Solid lubricants	Coatings, fillers, high-temperature applications
Molten salts, glass	Hot forming processes
Water, lipids, proteins	Biosystems, synovial joints
Water	Winter sports

Lubricants

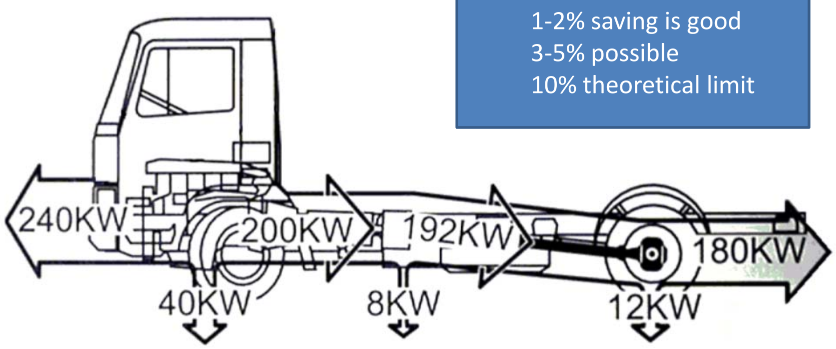
Main functions:

- *Lubricate*
- *Cool*
- *Clean*
- *Seal*
- *Protect from corrosion*

Automotive lubricants

- Engine oils
- Transmission lubricants
- Greases
- Hydraulic fluids

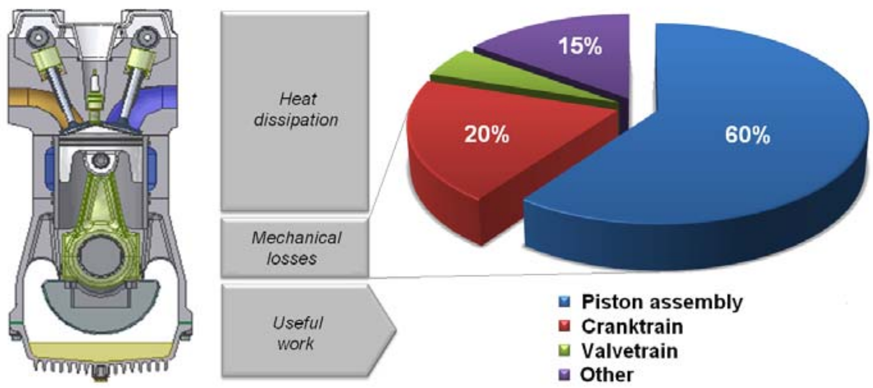
Energy losses in heavy-duty trucks



1-2% saving is good
3-5% possible
10% theoretical limit

- ✓ Thermal losses
- ✓ Friction losses in the powertrain
- ✓ Losses due to aerodynamic resistance, rolling friction, acceleration/braking cycles, etc

Energy losses in the engine



Mechanical losses: 90% viscous dissipation and 10% boundary friction.

Ways to better fuel economy

- New engines (FSI, TFSI, TSI)
- Lighter cars
- Thinner lubricants
- Low-friction coatings

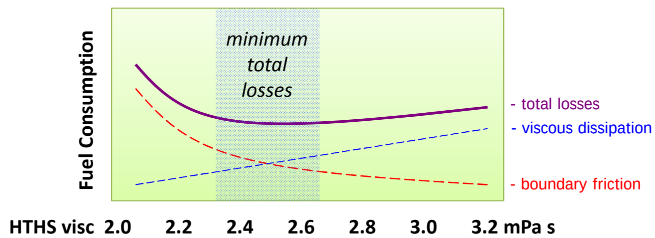
Volkswagen 180 hp 1.4-liter TSI engine has been declared the Engine the Year 2010.

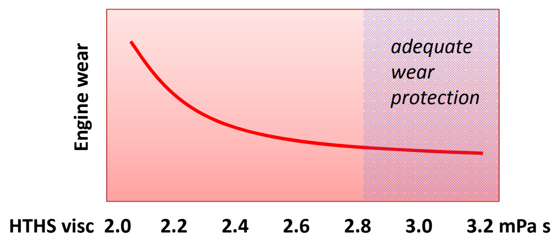
Lamborghini Sesto Elemento with a body made of CFRP, weighs just 999 kg. The vehicle powered by a 562 hp V10 engine and permanent all-wheel drive

15W-50 → 10W-40 → 5W-30 → 0W-20

Audi uses Al space frame for weight reduction

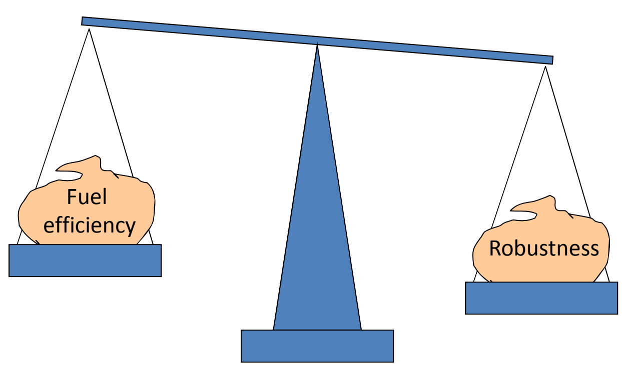
How thin we can go?





15W-50 (1970s) to 10W-40 (1990s) to 5W-30 (2000s) to 0W-20 (now?)

Friction vs wear



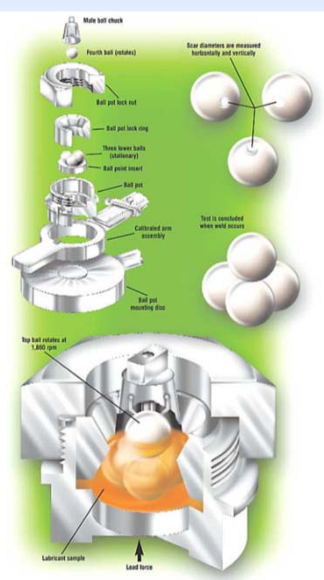
You may initially lock buyers by fuel economy claims, yet you risk expensive OEM recalls and long-term reputation damage if engines start to wear down prematurely

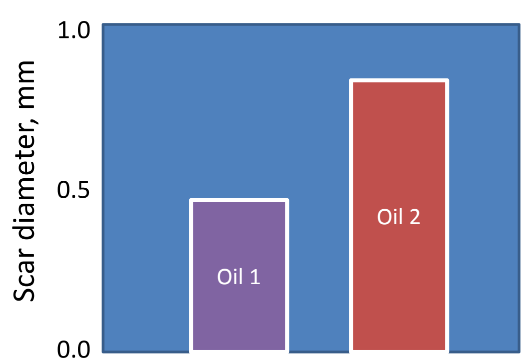
Most common tribotests

- 4-ball test
- Reciprocation friction and wear tester (ball on flat is the most common, e.g. HFRR)
- Ball on cylinder (BOCLE)
- Timken OK load
- Pin on disk
- Mini traction machine (MTM)
- Laboratory engine tests
- Field experience

give one-number performance scores

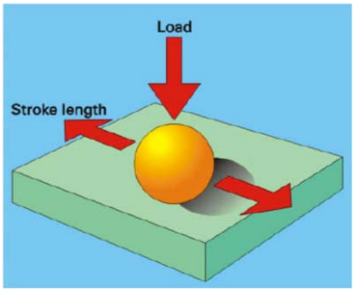
4-ball wear test (ASTM D4172)





12.7 mm balls, 1 hour, 40 kg load, 1800 rpm, 150^{o}C

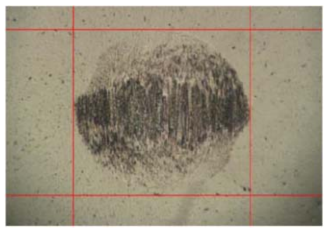
HFRR (ASTM D-6079, ISO-12156)



Test conditions:

Applied load	200 g ± 0.01 g
Stroke length	1 ± 0.02 mm
Frequency	50 ± 1 Hz
Test duration	75 ± 0.1 min
Fluid temperature	60 ± 2 °C
Fluid volume	2 ± 0.20 ml
Bath surface	6 ± 1 cm^2

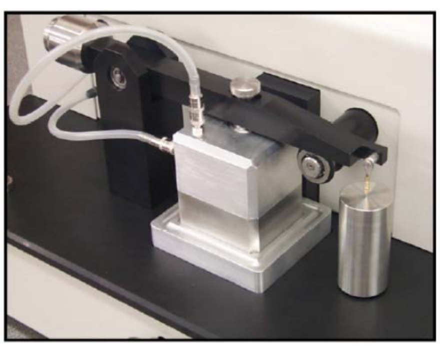
result

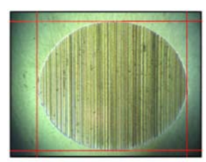


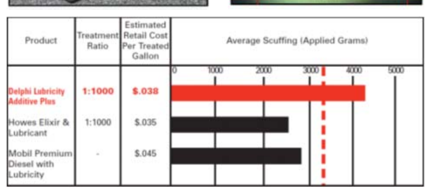
humidity corrected wear scar diameter WS1.4, in um

BOCLE (ASTM D-5001, D-6078)

Scuffing load ball-on-cylinder lubricity evaluator





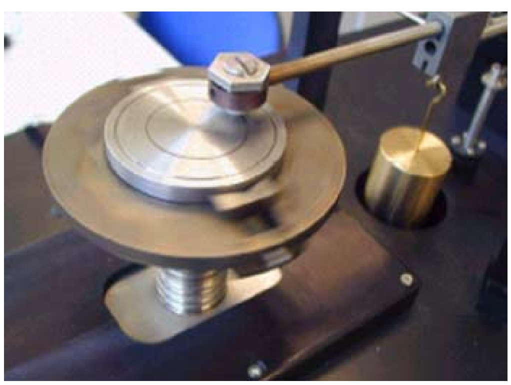


Flooded contact, 25^{o}C, 50%RH
12.7 mm ball is pressed against a cylinder rotating 525 rpm
Evaluated are:
SL-BOCLE: scuffing load, g
BOCLE: wear scar diameter, um

Timken OK load (ASTM D2509, 2782)

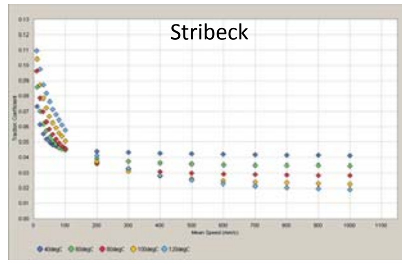
Setup:
- tapered roller bearing rotating at 800 rpm against a test steel block
- loading rate 1 kg/s
- test time: 10 min or until scoring detected
- 27°C (80°F), specified feed rate (45g/min) for lube or grease in study

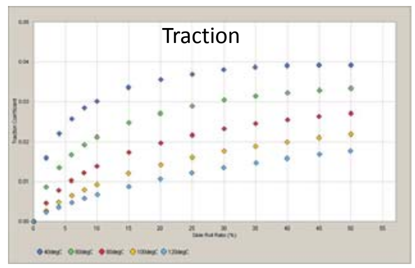
Pin-on-Disk



A variety of systems are available commercially
Macro-, micro- and nano-variants
Useful for wear tests on hard coatings
Optional moduli for special environments (oil, high temperature)
Core of ASTM G-99

MTM





- 19.05 mm (3/4 inch) ball on a 46 mm disc
- Mixed rolling/sliding contact
- 37 N load (1GPa)
- Sliding speed 0 to 2 m/s
- Sliding-rolling ratio SRR 0 to 50%
- Measure coefficient of traction (static C.O.F.) as a function of sliding velocity (Stribeck) and of SRR (Traction)

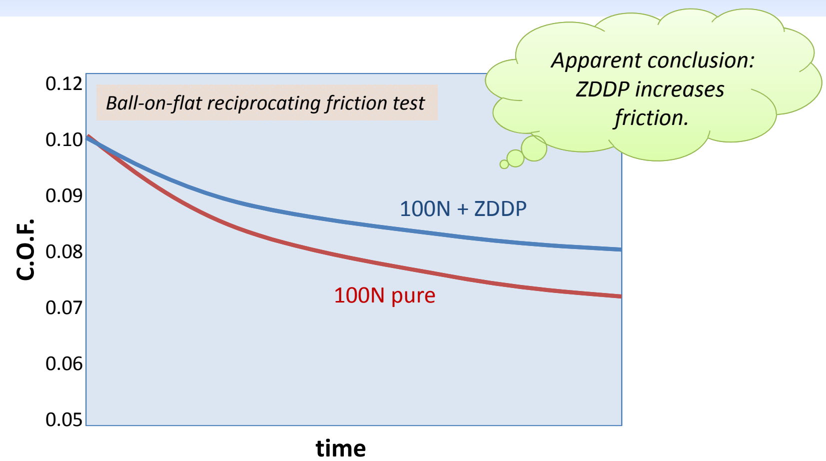
Keep it in mind

Not one single test can determine the lubricant's ability to function in real applications and many tests are done for specification and/or marketing purposes only.

If lubrication engineers and mechanical engineers were better educated in tribology and tribologists were better educated in lubrication engineering, many open technical problems of today related to friction and wear could have been solved a long time ago.

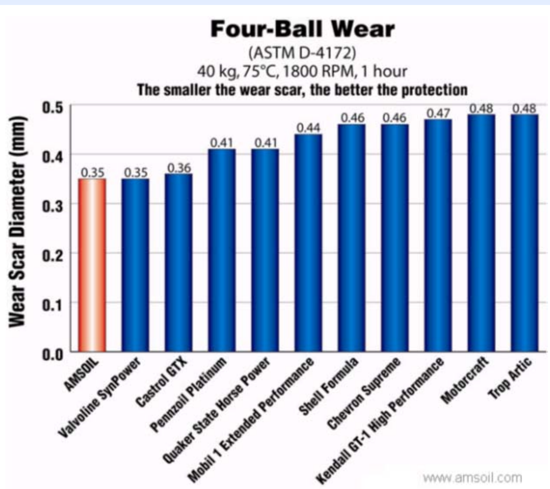
Mastering one specific test does not mean the tribology.

Avoid quick conclusions



Wrong! ZDDP reduces wear, hence the actual contact pressure in 100N + ZDDP at any given time is higher than in pure 100N. No conclusion on friction can be made unless wear is assessed.

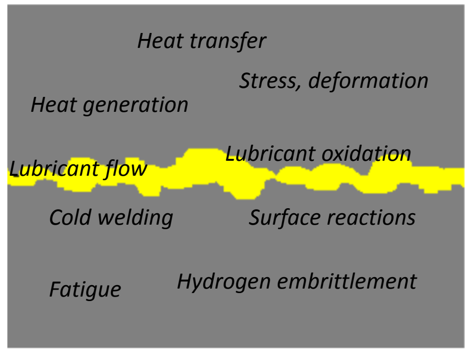
Be critical to what you are told



- Use of Mo thiophosphates is an easy and efficient way of “beating” the 4-ball test.
- Oxidative stress and humidity deplete Mo additive after ca 3000 km in field.
- For modern cars, the normal service interval is ca 30,000 km

Interdisciplinary contest

- Solid mechanics
- Fluid mechanics
- Rheology
- Phase transitions
- Heat and mass transfer
- Surface chemistry
- Chemical kinetics
- Thermodynamics



Tribology is the empirical science about friction and wear.

Getting closer to reality

There is little or no correlation between laboratory tests and field experience.

This necessitates development and use of application-specific tests, e.g.

API CJ-4 Sequence IIIF (ASTM D 6984)
A 1996/1997 231 C.I.D. (3800 CC) Series II General Motors V-6 fuel-injected gasoline engine is used. The engine runs a 10-minute initial oil leveling procedure followed by a 15-minute slow ramp up to speed and load conditions. It then operates at 100 bhp, 3600 rpm, and 155°C oil temperature for 80 hours, interrupted each 10-hours for oil level checks. At the end of the test, all six pistons are inspected for deposits and varnish; cam lobes and lifters are measured for wear.

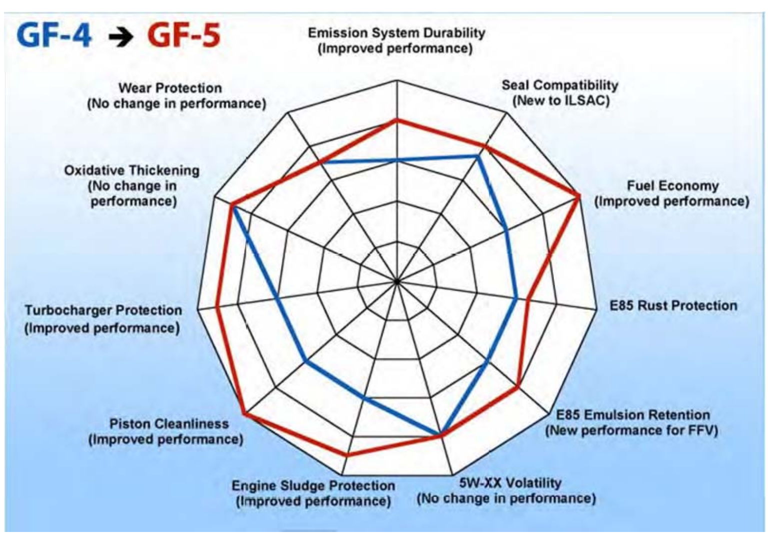
FZG Gear Wear (ASTM D4998)
FZG (*Forschungsstelle für Zahnräder und Getriebebau*) test evaluates gear tooth face wear-resisting capacity of gear lubricants.
The rig is operated at 100 rpm under constant load for 20 hours.
Gear tooth surface wear is visually rated and gear weight loss is measured.

ILSAC GF-4 tests

ILSAC - International Lubricant Standardization and Approval Committee

TEST	ASTM	OBJECTIVE
Ball Rust	D 6557	To evaluate the ability of an oil to prevent the formation of rust under short-trip service conditions.
Sequence IIIG	-	To measure oil thickening and piston deposits under high temperature conditions and to provide information about valve train wear.
Sequence IIIGA	-	To determine the cold-temperature viscosity performance of an end-of-test engine oil sample.
Sequence IVA	D 6891	To evaluate a lubricant's performance in preventing camshaft lobe wear in an overhead camshaft engine.
Sequence VG	D 6593	To evaluate a lubricant's performance in combating sludge and varnish formation in a modern engine.
Sequence VIB	D 6837	To measure the effects of automotive engine oils on the fuel economy of passenger cars and light-duty trucks equipped with a "low-friction" engine.
Sequence VIII	-	To evaluate a lubricant's performance in combating copper/lead/tin bearing corrosion and to measure viscous shear stability under high-temperature operating conditions using unleaded fuel.

Balancing multiple properties



Field is ultimate judge

Extensive lab testing and field trials conducted by well-equipped corporate tribology competence centers did not prevent:

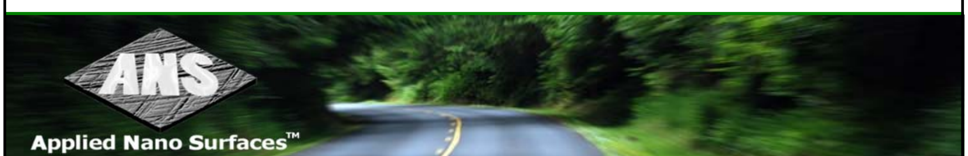
Failure of fuel pumps in diesel engines after switching to ULSD in the early 90s.

Failure of Nikasil coatings in BMW M52 and M60 engines 1993-1998.

Failure of GM's 4T65EV/GT transmissions in Volvo XC90 T6 models 2003-2004.

etc.

Tribologists are not going to stay without job in the nearest future!



Part II:

Energy-saving lubricants and low-friction coatings

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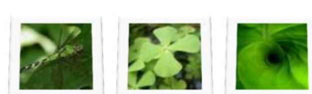
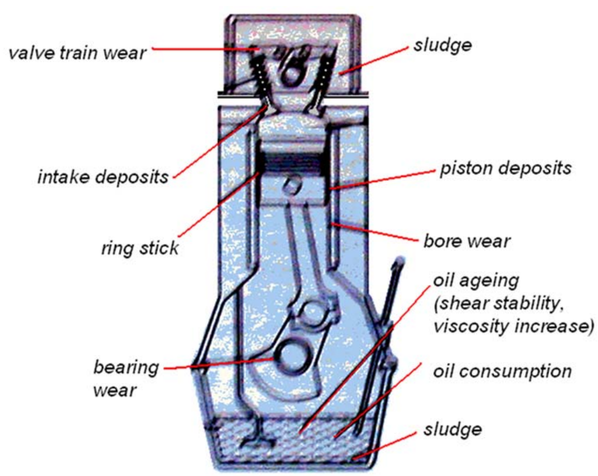


What is an engine oil

Engine Oil = Base oil + Additives + Trade name

Functions of engine oil

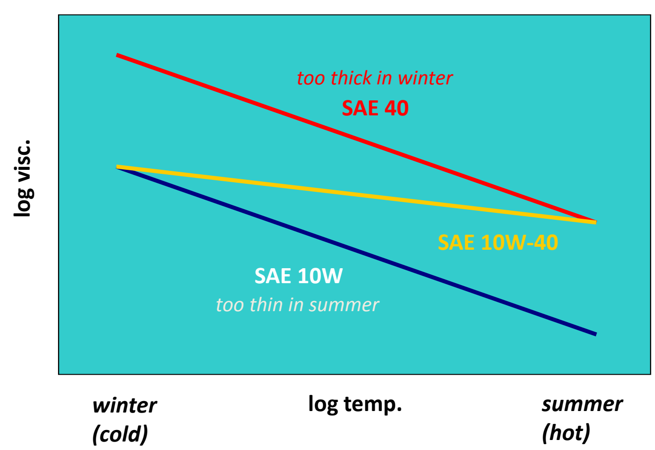


Viscosity grading

SAE viscosity grade	Low. temp. cranking viscosity (mPa s) max, CCS	Low.temp. pumping viscosity (mPa s) max, MRV	Low shear rate kin. viscosity at 100°C min (cSt)	Low shear rate kin. viscosity at 100°C max (cSt)	High shear rate visc. at 150°C and 10^6 s^{-1} min (mPa s)
0 W	3250 / -30°C	60000 / -40°C	3.8		
5 W	3500 / -25°C	60000 / -35°C	3.8		
10 W	3500 / -20°C	60000 / -30°C	4.1		
15 W	3500 / -15°C	60000 / -25°C	5.6		
20 W	4500 / -10°C	60000 / -20°C	5.6		
25 W	6000 / -5°C	60000 / -15°C	9.3		
20			5.6	< 9.3	2.6
30			9.3	< 12.5	2.9
40[1]			12.5	< 16.3	2.9
40[2]			12.5	< 16.3	3.7
50			16.3	< 21.9	3.7
60			21.9	< 26.1	3.7

[1] for 0W, 5W, 10W
[2] for 15W, 20W, 25W and monogrades

Multigrades



Base oil

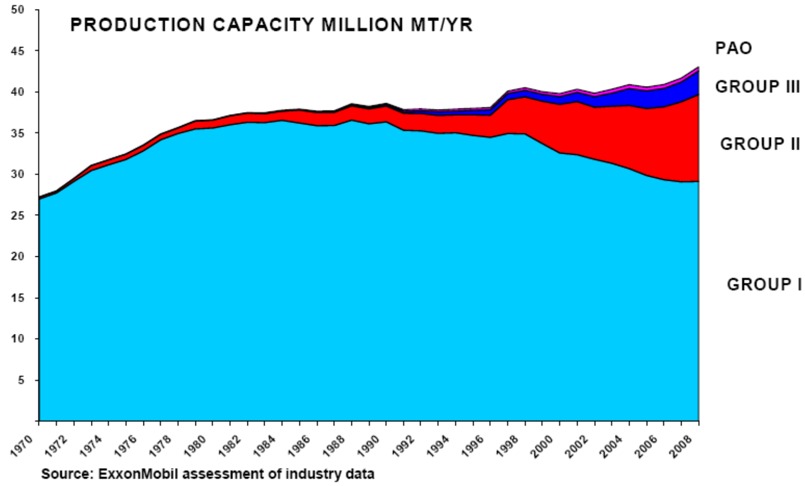
Base oils	Sulfur	Aromaticity	VI
API Group I (solvent refined)	> 0.03%	> 10%	80-120
API Group II (hydroprocessed)	< 0.03%	< 10%	80-120
API Group III (hydroprocessed/isodewaxed)	< 0.03%	< 10%	120-160
API Group IV (synthetic PAO)	0	0	120-160

Other base oils: naphthenics
alkylaromates
polybutenes
synthetic esters (Group V)

Additives

Additive	Chemical nature
Antioxidants	ZnDTP, hindered phenols, diarylamines, alkylsulfides, disulfides, phosphites
VI improvers	olefin copolymers, styrene-butadiene copolymers, polyalkyl methacrylates
Pour point depressants	polyalkyl methacrylates
TBN buffer, detergents, dispersants	phenates, thiophosphonates, sulfonates, ashless dispersants
EP additives, AW additives, friction modifiers	dithiophosphates, phosphate esters, borate esters, polysulfides, molybdenum derivatives, fatty esters

Trends in base oil production



Non-tribological aspects

- ✓ Base oil production is driven by regional fuel demand.
- ✓ Group II and Group III oils have similar processing schemes, but are made from different feed based on fuel production.
- ✓ Group II is produced using vacuum gas oil in a base oil hydrocracker in gasoline production (North America).
- ✓ Group III is produced from unconverted oil from a two-stage diesel hydrocracker (Asia, the Middle East, Eastern Europe).
- ✓ Engine manufacturers require *global availability* of *fungible base stocks* from *multiple plants*.

Oil is not always oily

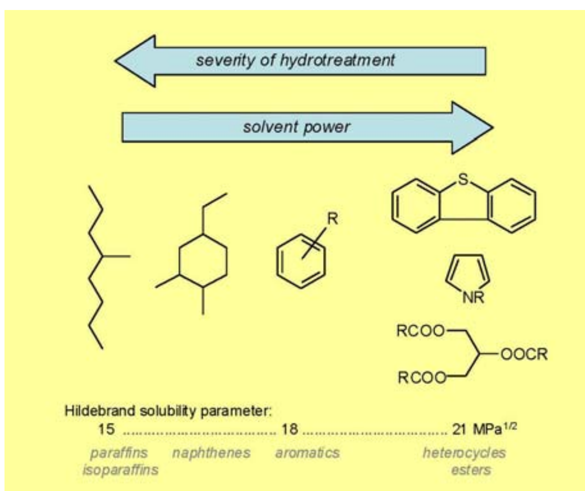

Tribological performance of ionised vegetable oils as lubricity and fatty oiliness additives in lubricants and fuels

ABSTRACT

INTRODUCTION


Elektrionized™ Vegetable Oils as Lubricity Components in Metalworking Lubricants

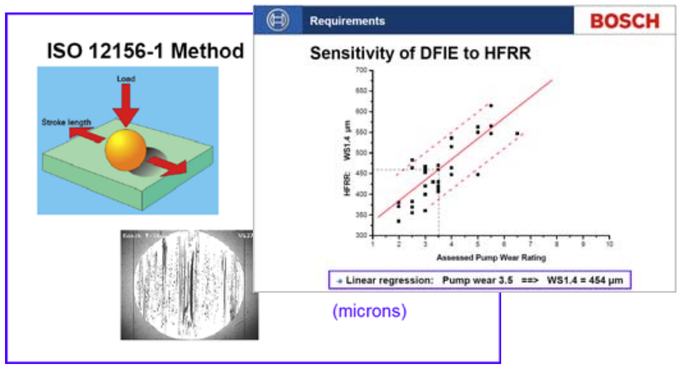
Refining reduces lubricity



Lubricity challenge

"For Diesel Fuel Injection Equipment (DFIE) lubricity is the most valuable and crucial property"

Klaus Meyer and Thomas C. Livingston, Robert Bosch GmbH
CARB Fuels Workshop, Sacramento, CA, Feb. 20, 2003

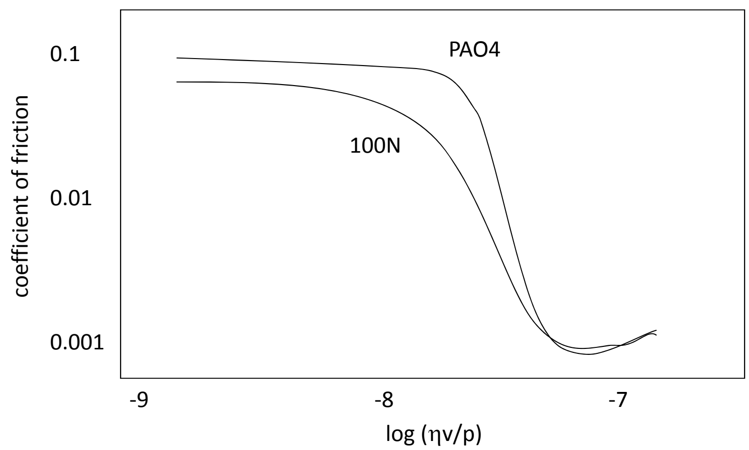


Pros and cons of base oil interchange

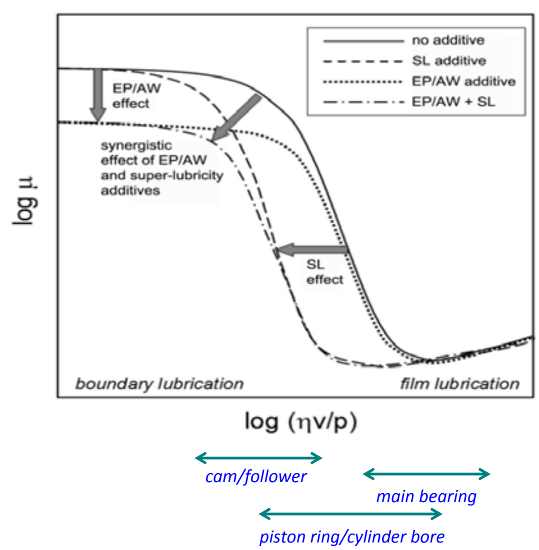
When changing from API Group I to API Group II and III

Expect improvement in:	*Expect deterioration in:*
VI Noack volatility Pour point Response to antioxidants Sulfur content Sludge	Solubility and dispersancy Seal compatibility index (SCI) Lubricity

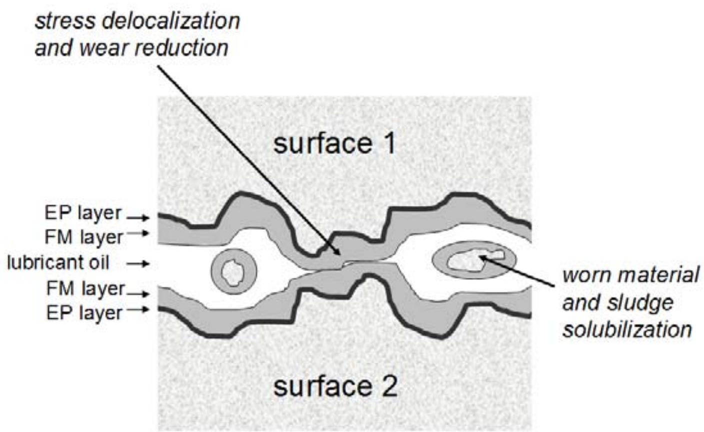
Lubricity contest: PAO4 vs 100N



EP/AW and lubricity additives



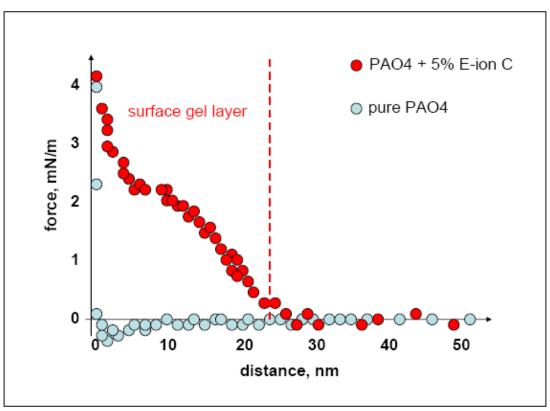
Superlubricity



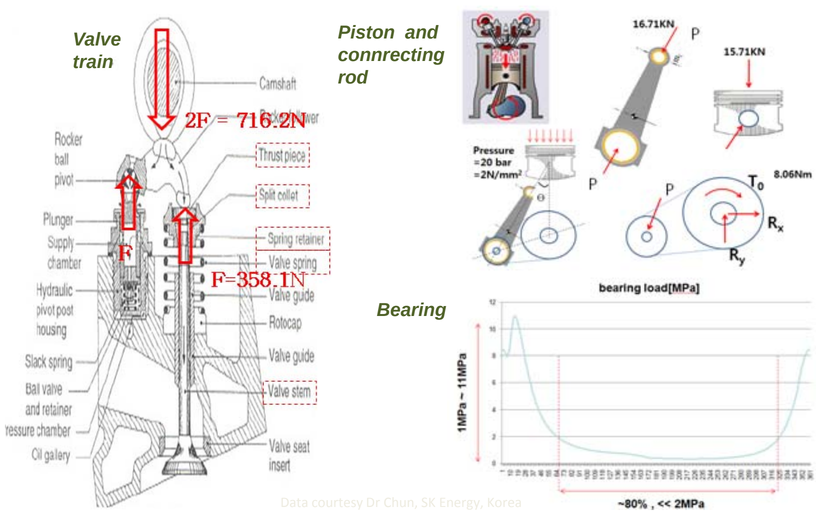
• Improved lubricant film strength due to surface gel formation
• Prevents film failure at dead points (stick-slip and chatter control)

AFM of adsorbed SLA layers

AFM



Tribological conditions in engine



Fuel economy in focus

Volvo V70, 1997
2.4 L, 170 hp, 220 N/m
Kerb weight: 1434 kg
Fuel consumption:
15.2 - 7.9 - 10,6 L/100 km

Volvo V70, 2006
2.4 L, 170 hp, 225 N/m
Kerb weight: 1495 kg
Fuel consumption:
12.6 - 7.2 - 9.2 L/100 km

10% fuel economy achieved in 10 years

Fuel saving

- **Powertrain optimisation** (ca 5% efficiency gain)

- **Improved car aerodynamics** (important for motorway driving)

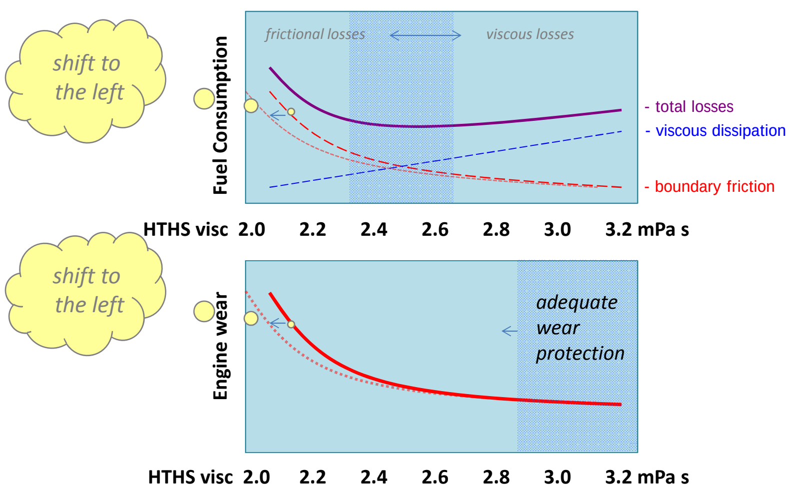
- **Fuel economy engine oil**:

In the past decade, 1990s, Castrol GTX 10W-40 (A3/B3), visc.& 100°C 12.5 - 16.3 cSt
Nowadays, it is Castrol SLX Longtec 0W-30 (A5/B5), visc.& 100°C 9.3 – 12.5 cSt.

Viscous dissipation ∝ visc reduced by 14/11 ≈ 1.3 times giving ca 3% savings.
Friction reducing additives reduce frictional losses at low rpm (city driving), ca 2% savings.

Developments on the oil side account for less than 5% fuel savings in 10 years!

Boundary lubricity additives



Boundary lubricity additives allow safe transition to lower viscosity oils

Oil performance assessment

A large number of laboratory engine tests exist:

- Sequence L38 (ILSAC GF-2)
- Sequences IIIF, VE and VIII (ILSAC GF-3)
- Sequences IIIG (API CJ-4), VG and IVA (ILSAC GF-4)

Key performance criteria:

- engine cleanliness;
- component wear
- oil characteristics (oxidation, viscosity change)
- fuel efficiency

GF5 requires oils with reduced ZnDTP content.

Surface engineering

Surface polishing
— Reduces asperity friction

Surface texturing
— Creates dimples or grooves in surface for better oil retention

PVD, CVD, PTWA thermal spray
— Hard surface coatings such as DLC, CrN, TaC, TiB_2, WC, etc.
— Self-lubricated coatings
— Iron coatings on Al substrates
— Focus on wear resistance

Phosphatation, nitriding and nitrocarburation
— Create phosphate, nitride or carbide layers for hardness, antiwelding, and oil film adhesion

Triboconditioning
— A dedicated finishing operation utilizing in-manufacture running-in (mechanochemical treatment) of components

Hard coatings vs soft coatings

Hard coatings
DLC, TiN, CrN, WC, etc.

Soft coatings
MoS_2, WS_2, graphite, Teflon

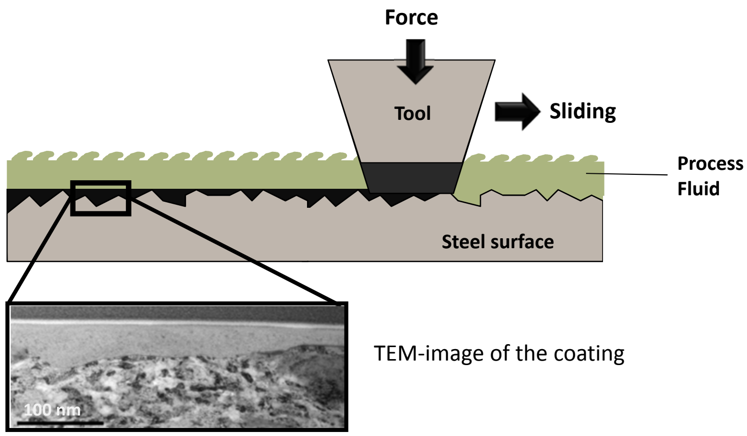
Composite coatings
WS_2/DLC
MoS_2/Ti
Cu/Teflon
SiC/Ni

Hard coatings and friction

- ✓ Hard coatings are primarily designed to serve as ANTIWEAR coatings.
- ✓ The fact that DLC coating reduces C.O.F. from 0.3 to 0.15 in a dry steel-steel contact DOES NOT mean that it is going to reduce C.O.F. from 0.1 to 0.05 in a lubricated contact.
- ✓ By inhibiting action of lubricity additives, hard coatings may initiate earlier transition from full film to boundary lubrication regime.
- ✓ Hard coatings may cause abrasive wear of counter-surface in the tribocontact.

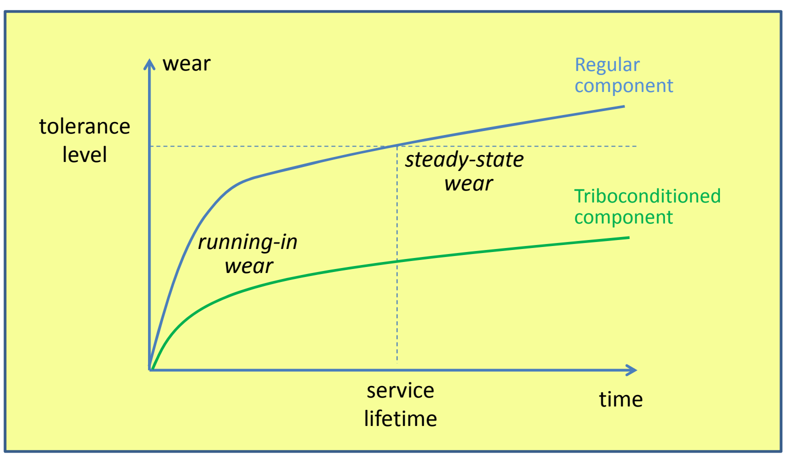
"*Antiwear*" is not synonymous with "*Antifriction*"

ANS triboconditioning



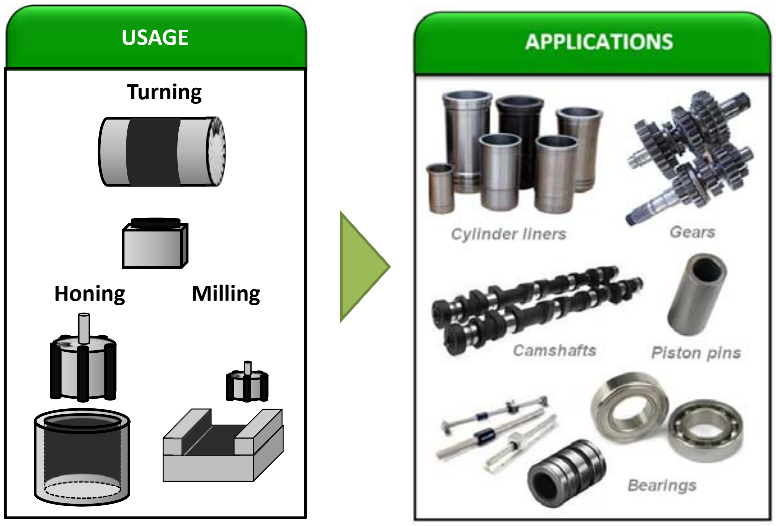
- ANS triboconditioning™ is a dedicated surface finishing method for improving the tribological properties of mechanical parts
- It combines in-manufacture running-in with tribodeposition of a low-friction antiwear film

Tribology of triboconditioning

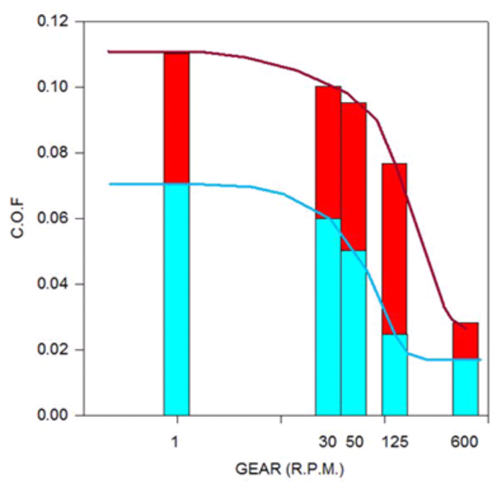


- Improved surface finish and surface integrity
- Compressive stress build-up
- Reduced tribomutation during running-in
- Improved lubricant film strength

Applications



Friction and wear reduction



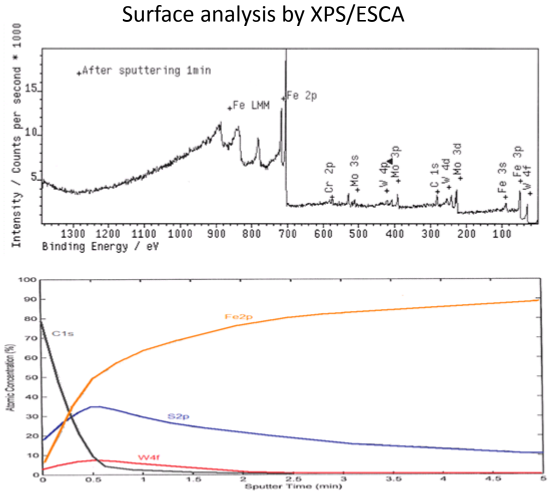
untreated surface

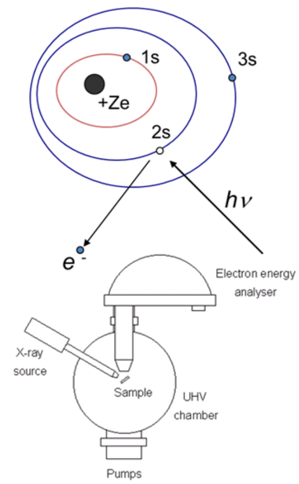
triboconditioned surface

- ✓ Reduction in friction 20 to 60%
- ✓ Reduction in wear 4 to 10 times.

WS_2 in tribofilms

Surface analysis by XPS/ESCA





ANS process generates 10-50 nm WS_2 tribofilm improving the tribological properties

Conclusions

The major developments leading towards improved fuel efficiency are:

- Powertrain optimization and curb weight reduction
- Use of energy-efficient lubricants
- Use of antifriction coatings

Antifriction coatings reduce dependency on additive package in oils allowing safe transition to environmentally-savvy low-viscosity lubricants with reduced additive content.