Fuel economy in focus: advances in development of energy-efficient lubricants and low-friction coatings for automotive applications

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Meeting the challenge

New fuel economy standards for automobiles erected by governments in the G20 major economies and change in customer preferences driven by high fuel prices put increased pressure on car makers. Thus, the U.S. Environmental Protection Agency is preparing to look at standards for 2017 and beyond - setting at the top of its potential range a standard of 62 mpg by 2025. In one or another way, those political and economical incentives intensify research and development efforts taken by major OEMs in order to achieve new ambitious fuel economy targets. Apart from engineering efforts on use of alternative energy sources to reduce green house gas emissions, use of new materials to reduce vehicle weight, development of hybrid cars, and continuing powertrain optimisation, a big emphasis is made on understanding tribological aspects of energy losses in powertrain and utilising current advancements in lubrication engineering and coatings to fight those losses. Indeed, friction and wear are inherent in operation of any machines and mechanisms. The majority of machines and mechanisms can be viewed as complex tribosystems containing mechanical parts and lubricant. Correspondingly, friction and wear can conceptually be controlled in three different ways:

- On the material side - by choosing lighter and durable materials with appropriate mechanical and tribological properties in manufacturing of mechanical parts;
- On the coating side - by improving tribological behavior of existing materials by means of surface coatings;
- On the lubricant side - by developing lubricants to obtain desired tribological behavior for a given material.

Development costs, material costs and production costs are always important factors when market potential of one or another approach is to be assessed.

Smarter engines, lighter cars

Engineering advancements in car construction over the past decades did not come unnoticed: the average fuel consumption, normalised to engine output, dropped from 10L / 100 km in the 1980s to 5L / 100 km nowadays. Most noticeable developments are broad acceptance of fuel stratified injection (FSI) direct injection technology. Though FSI technology has been around for at least half a century, its advantages could not be fully realized until electronic engine control modules become available. FSI technology increases the torque and power of spark-ignition engines, makes them as much as 15 percent more economical at a given power output. The motor industry in Europe and North America has now switched completely to direct fuelling for the new petrol engines it is introducing. The majority of modern FSI engines are actually turbo-FSI (TFSI or TSI) as they combine direct injection with twincharging - a turbocharger and a supercharger working together.

In a FSI engine, the fuel is injected into the cylinder just before ignition. This allows for higher compression ratios without knocking, and leaner air/fuel mixtures than in conventional Otto-cycle internal combustion engines. By regulating injection pressure and valve timing and lift, constant electronically-aided engine efficiency tuning is possible based on the actual load, fuel type, exhaust parameters, and ambient conditions.

An alternative to FSI is homogeneous charge compression ignition (HCCI) technology which can be viewed as a hybrid of homogeneous charge spark ignition (in gasoline engines) and stratified charge compression ignition (in diesel engines). In theory, HCCI allows one to achieve gasoline engine-like emissions along with diesel engine-like efficiency. Analogously to diesel engines, in an HCCI engine, the air/fuel mixture is ignited due to compression without using an electric discharge. Stratified charge compression ignition in diesel engines also relies on temperature and density increase resulting from compression, but combustion occurs at the boundary of fuel-air mixing, caused by an injection event, to initiate combustion. Inherently, HCCI engines are more difficult to control than other modern combustion engines, and to date, there have only been a few prototype engines running in the HCCI mode. Recently, a vehicle powered by 25 cc 1.3 hp HCCI engine deploying WS^2 antifriction coating was constructed by Royal Institute of Technology KTH, Stockholm, Sweden (Figure 1)

__Figure 1__ Is that what the car of the future will look like? Agelis ecocar built at Royal Institute of Technology, KTH, Stockholm, Sweden, managed to run for 481 km at 1 L of gasoline during Shell Eco Marathon 2010. Critical engine components had antifriction coatings made by Applied Nano Surfaces and a fuel-economy engine oil produced by Elektrion s.a. was used.

Apart from engine development, improving efficiency of power transmission is another way towards better fuel economy: continuously variable transmissions and automatic gearboxes with 6 to 8 speeds are getting increasingly common.

As the use of new materials is concerned, the main focus is on reducing the car weight while keeping manufacturing costs down. On this frontier, quite drastic changes can be observed over past two decades. Aluminium engine blocks have become a standard in passenger cars and other small vehicles. The move to aluminium was primarily motivated by curb weight reduction. Some luxury cars, e.g. Audi A8 and R8, Jaguar XJ, BMW 7, have significant part of their body made of aluminium in order to further reduce the weight and improve performance of the vehicles. If the price does not matter, even more weight loss can be achieved: super sport cars such as Koenigsegg, Bugatti and Lamborghini have certain parts of body construction made of carbon fiber or carbon-fiber reinforced plastics (CFRP). Thus, Lamborghini has recently unveiled its Sesto Elemento concept supercar at the 2010 Paris Motor Show. The name "Sesto Elemento" originates from the atomic number of carbon in the periodic table, reflecting the fact that a great deal of the vehicle is constructed from CFRP.

__Figure 2__ Engineering marvel or an exercise in extreme weight loss? Lamborghini Sesto Elemento super sport car has a body constructed of CFRP, resulting in a curb weight of just 999 kg for the vehicle powered by 562 hp V10 engine and permanent all-wheel drive (Photo courtesy Autoguide.com).

Another noteworthy advancement on the material side is the use of lightweight porous metals and composites as impact energy absorbers and sound-damping elements.

Antifriction coatings

In an internal combustion engine, ca 15% of energy is lost due to friction [1-2]. This 15% can be further subdivided, in a proportion 9:1, into a dissipative part (viscous dissipation due to lubricant flow) and a frictional part (mostly due to boundary friction in piston ring/cylinder bore, cranktrain and valvetrain systems). The dissipative losses can be reduced by using lower-viscosity oils and smaller displacement volumes. The frictional part can be reduced by using antifriction coatings on performance-critical parts as well as by deploying special friction-reducing additives in engine oil. Unfortunately, use of additives in oil may cause exhaust catalyst poisoning and so must be constrained. Thus, the phosphorus content in ILSAC GF5 engine oils must not exceed 800 ppm. This makes coatings an attractive alternative, minimising the dependence of additives.

Nowadays, various coatings are used in automotive engineering to compensate deficiencies of bulk materials. Coatings can be used to improve wear resistance, corrosion resistance, appearance, adhesive properties, etc. For instance, Nikasil, Alusil or wire-arc sprayed iron coatings are used for reinforcement of cylinder bore walls and improved oil film retention in aluminium engines. Other classical methods used for enhancing the tribological properties of various automotive components are chrome plating, ferritic nitrocarburation and phosphatation.

Ironically, whenever advancements in coatings are discussed in automotive engineering perspective, one often tends to focus exclusively on hard antiwear coatings such as diamond-like carbon (DLC), boron nitride (BN), silicon carbide (SiC), titanium nitride (TiN), tungsten carbide (WC), etc. This is probably explained by the fact that, from the car owner perspective at least, an engine which wears prematurely is a much worse choice than a robust engine which has marginally higher fuel consumption.

The development of the hard coatings started in the 1960s with the chemical (CVD) and physical (PVD) vapor deposition techniques. There are many PVD variants in use today (magnetron sputtering, evaporation by laser, wire arc, electron beam, etc.). Hard coatings have many unique properties, such as chemical inertness and extreme resistance against abrasion, making them invaluable in the tooling industry. Notwithstanding their impressive antiwear performance, hard coatings help little to improve fuel economy: the fact that DLC coatings afford a reduction of the coefficient of friction from 0.3 to 0.15 in a dry steel-vs-steel contact does not mean one is going to enjoy a 50% friction reduction in an engine where all moving parts are lubricated and the characteristic value of the coefficient of friction is already well below 0.1. As a matter of fact, hard coatings may increase friction by inhibiting the effect of lubricity additives in oil.

Antifriction coatings serve that specific goal: to reduce friction, thereby minimising dependence on the additive package. In an attempt to combine the mechanical toughness of hard coatings with high lubricity, composite PVD coatings such as Balenit C (WC/C, Balzers Ltd) and MoST (MoS_2/Ti, Teer Coatings Ltd) exhibiting self-lubricating properties have been developed.

Soft sacrificial coatings represent a fundamentally different philosophy in the development of antifriction and antiwear coatings: the coating can be sacrificed in action while protecting the coated parts. Molybdenum disulfide (MoS_2) coatings were pioneered by Alfa Molykote after the Second World War. After acquisition of Molykote in 1964, Dow Corning developed and manufactured a few lines of Molykote solid lubricant coatings. Molykote coatings are based on MoS_2 as the main friction-reducing component, but they may contain a number of other ingredients such as graphite, resin binder, corrosion inhibitor, etc. required to control consistency, adhesion, corrosion resistance, appearance and other properties. A similar concept has been used in the development of EcoTough coatings for piston skirt by Federal-Mogul Corporation. The EcoTough coating consists of a blend of graphite, carbon fibre, and molybdenum disulfide bound in a resin binder and is claimed to provide superior friction reduction and scuff resistance. Tungsten disulfide (WS_2) is another member of layered transition metal dichalcogenides (LTMD) used as a substitute for MoS_2 in aeronautics and spacecraft industry. As compared to MoS_2, WS_2 has superior high temperature performance and is less sensitive to humidity. Applied Nano Surfaces (ANS) is a young Swedish company which has pioneered a revolutionary new technology for friction and wear reduction using WS_2-based tribocoatings.

The ANS technology, known as ANS triboconditioning, is a dedicated metalworking process that combines elements of extreme-pressure mechanical burnishing of the component surface with a tribochemical, or mechanochemical, deposition of a low-friction antiwear film of WS_2. The mechanical treatment is essential for improving the surface finish by leveling off asperities and building up compressive stresses within the underlying material layer, and for initiating the triboreaction that leads to the in-situ formation and interfacial nucleation of tungsten disulfide onto the said surface. This gives a smoother surface with significantly reduced coefficient of boundary friction and improved wear-resistance.

The ANS coatings exhibit the superlubricity effect by simultaneously shifting the Stribeck diagram down (by lowering friction in the boundary zone) and to the left (by extending the film lubrication regime towards higher loads). The outstanding wear-resistance of ANS-coated parts allows one to switch to lower viscosity lubricants for improved energy efficiency without accruing risk of wear-related failures.

When applied to components made of steel or cast iron, such as cylinder liners, camshafts, piston pins, gears, etc., the ANS process significantly improves their tribological performance with the coefficient of boundary friction being reduced by 20 to 60%, and wear reduced by 4 to 10 times.

Though antifriction coatings give obvious performance advantages, carmakers are often reluctant to experiment with new things: One engineering corollary of the Murphy's law is that, whenever you attempt to upgrade something, something else is invariably going to be degraded. This has proven true for BMW following the introduction of aluminium engines with Nikasil coatings. The high sulphur content in the fuel in North America, Asia and UK caused corrosion of the Nikasil lining in the cylinders, leading to excessive bore wear and a loss of compression just after a couple of years of exploitation.

Energy efficient lubricants

Since a significant part of energy losses in the internal combustion engine comes from viscous dissipation, there is an obvious trend towards low-viscosity oils, from SAE 40 and 50 viscosity grades in the 1960-1980s to SAE 20 and 30 nowadays. The transition has been facilitated by availability of high-quality hydroprocessed and synthetic base oils [3]. Due to their greatly reduced volatility and good low-temperature performance, modern base oils of API Group II-IV allow the formulation of lighter automotive of 0W-30, 0W-20, or even lighter grades, to achieve better fuel economy. However, as explained in Figure 4, the use of thinner base oils increases the risk of engine wear unless appropriate antiwear additives are simultaneously deployed in the formulations or protective antiwear coatings deployed on wear-critical engine components.

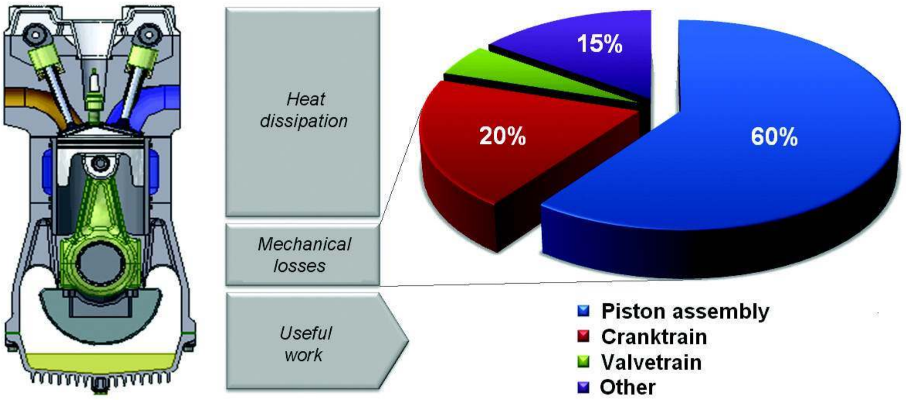


Figure 3 *Approximate distribution of energy losses within the internal combustion engine.*

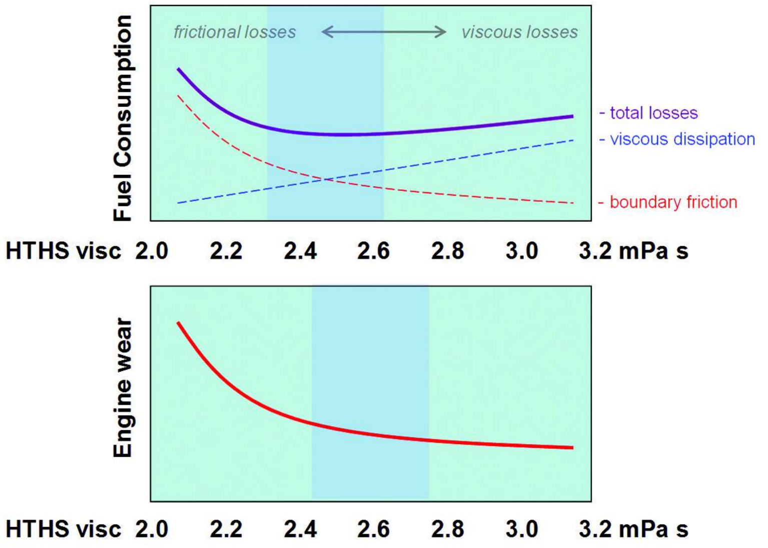
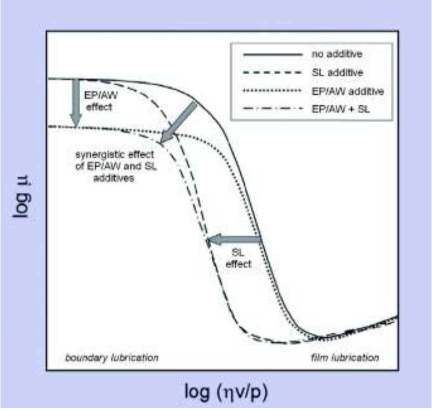


Figure 4 *Dependence on high-temperature high-shear viscosity of boundary friction and viscous dissipation components contributing to the mechanical energy loss in the internal combustion engine (top) and of engine wear speed (bottom).*

Extreme pressure antiwear (EP/AW) additives reduce friction and wear by chemically reacting to the metal surface under boundary contact conditions to yield a reaction product which prevents cold welding. Unlike conventional EP/AW additives, such as sulphurised olefins, tricresylphosphate and zinc dialkyldithiophosphate, which chemically react with metal surfaces when a direct asperity-asperity contact occurs in the boundary lubrication regime, boundary lubricity additives function by physical adsorption onto the rubbing surfaces. In other words, boundary lubricity additives reduce friction and wear by forming adsorbed surface layers (fatty amides, esters) or slippery surface deposits (graphite, Teflon, MoS_2), which physically separate the rubbing surfaces from each other, while EP/AW additives start to act after the asperity-asperity contact has occurred - but they do not prevent its occurrence. Boundary lubricity additives keep their lubricity-enhancing effect, even if there is no reciprocal motion between the rubbing surfaces. That is why they are so efficient in controlling stick-slip and chatter phenomena. It is important to realise that many additives are multifunctional – for instance, sulphurised olefins, borate esters and phosphate esters have both boundary lubricity and EP/AW functions.



One special class of boundary lubricity additives falls outside the existing classification - we call them surface-gel-forming friction modifiers or superlubricity additives. Examples are certain amphiphilic ester-based comb-copolymers and Elektrionised vegetable oils [4]. These additives form a sponge-like viscoelastic surface layer retaining the base oil in the tribocontact even at zero sliding speed (zero Hersey number), thus expanding the range of operating conditions under which film lubrication is sustained.

Superlubricity additives build upon the concept of biomimetic lubrication. Most readers of this article have probably experienced such a superlubricity effect while walking on the slippery rocks of the seashore. What makes those rocks so slippery is the algae slime growing on the rock surface. The algae slime retains a sufficiently thick layer of water between your feet and the rock surface to enable transition from boundary to film lubrication regime under the pressure (equal to your body weight divided by the area of your footstep) when water alone would fail to provide adequate film strength.

As explained in Figure 5, by shifting the Stribeck curve to the left, friction modifiers cause an equivalent shift of the wear and the frictional losses curves in Figure 4. The result is that the optimal viscosity range (shaded in blue) corresponding to the greatest fuel economy is shifted to the left.

Conclusions

The major developments leading towards improved fuel efficiency of automobiles over past decades are:

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

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