A GENERAL OVERVIEW ON PERFORMANT AND COST – SAVING SOLUTIONS IN DESIGNING COATINGS FOR FUEL INJECTION SYSTEMS

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Abstract. According to C. Treutler [1], in Europe, more than 40% of all new cars are equipped with Diesel engines, including also the high class cars. High-pressure injection systems with pressure values up to 2000 bar (200 MPa) give the best results for combustion. At the same time, high - hard carbon coatings hold the key to improved performance for these kinds of systems. Regarding this, Diamond-like carbon (DLC)-coatings present crucial advantages in terms of tribological properties (low friction coefficient and low wear for both coated part and counter body). Using a cheaper variant of alloyed steel for manufacturing fuel injection parts and combining it with a DLC deposition, the results could be very performing in terms of quality – cost aspects. Specially designed plasma processes for DLC coatings deposition allow keeping the component temperature below 200°C, in order to not modify by annealing the structure of steel used and to decrease its hardness. This paper represents a theoretical study of a debutant Ph.D. students group and it aims to present a general overview regarding some advantages of using DLC films; at the same time, there are presented few practical applications of these kinds of films in manufacturing certain parts of Diesel fuel injection systems.

Keywords: fuel injection system, DLC coatings, tribology, efficient solutions

1. Introduction

If we look at the applications today, it is fair to say that all majorities of diesel cars that have common rail or high-pressure injection use this type of coating technology on their diesel injection components. According to http://vehicle-engineer.com site, this technology was first used some ten years ago on the Volkswagen TDI engine, and this Diamond-like Carbon (DLC) coating technology has been constantly fine tuned during the last decade through both motorsport and production vehicle applications.

For modern environmentally friendly cars, we need engines with low emissions and with reduced fuel consumption.

On the other hand, we would like to have a fun driving experience and we want to buy the car at the lowest price possible. Gasoline and diesel fuel injection systems provide the basis for the car manufacturer to fulfil these targets.

Diesel engines have a higher degree of efficiency in their use of the fuel energy. In Europe, more than 40% of all new cars are equipped with a diesel engine, including high-class cars [1].

According to the research in the field and different practical applications, High-pressure injection systems with pressures up to 2000 bar (200 MPa) give the best results for combustion [1].

The challenges for high-pressure pumps for passenger cars are the high pressure of up to 2000 bar (200 MPa), low power consumption, lightweight, low noise and long lifetime.

For low cost reasons, it should not need a separate lubrication system. Unfortunately, the quality of diesel fuel differs concerning the ability to lubricate a mechanical contact of different components. Therefore, we need solid lubricant coatings for several parts to protect them from friction and wear [1, 2].

Thin film coatings, deposited by the help of plasma technology, are very hard and wear-resistant. Intense plasma cleaning and ion bombardment during deposition result in excellent adhesion and high density of the films.

Thin films are highly suitable for parts with low tolerances.

Specially designed plasma processes allow keeping the component temperature below 200^{o}C in order not to anneal the steel used and decrease its hardness.

On the other hand, the need for a moderate temperature of the parts to be coated will limit the high deposition rate [1, 3].

DLC coatings have brought valuable cost-efficient benefits to engines in both the racing and automotive markets, and as such we anticipate that we will see DLC coatings used more and more in both of these industries.

According to C. Treutler [1], for the protection of component parts against friction and wear, diamond-like-carbon (DLC)-coatings show crucial advantages in a low wear, in the low coefficient of friction (even for a non lubricated contact with steel as counterpart) and in the low wear of the counter body.

Hence, for example, only the pump piston needs to be coated and not the inner surface of the pump cylinder, which would be very difficult. Besides this, the costs for the coating of the counterpart can be saved [1].

Despite the current economic crisis, it is essential for the industry and market leaders to start contemplating the recovery [13].

These leaders need to determine how their company and products will be profiled during the recovery to make sure they are back on track when business picks up again.

The European Commission has recently developed a programme to reduce vehicle CO_2 emissions, which motor manufacturers must adhere too. Failure to meet these emission limits will in the future result in financial penalties of at least €95 per gram above the limit set by the EC [13].

Many studies showed that using DLC coatings reduces the friction losses, which translates into reduced consumption and, subsequently, lower emissions. Essentially, this means that DLC coatings will be one way to help meet future CO_2 limits.

PSA Peugeot Citroën (previously Peugeot Société Anonyme - PSA Group) conducted a test to measure the actual value of DLC coatings in this process. It revealed that DLC coatings applied on tappets reduce overall fuel consumption by 1-2%, which equates to a saving of somewhere between 2-3g/km of CO_2 [13].

The biggest advantage of DLC coatings is that they reduce CO_2 emissions in existing engines, so there is no need for a drastic redesign of the engine. Like an example, tappets can be coated, which can lead to a 1-2% reduction of emissions without a redesign of the valve-train.

According to Mark Boghe [13] (Bekaert DLC coatings), if a manufacturer wants to take full advantage of this technology, however, these coatings need to be integrated from the start of the design. At the same time, by applying DLC coatings to components not only increases the lifetime of the components, but also extends the lifetime of the entire engine.

Considering a camshaft, by applying a DLC coating, the profile of the cams is protected against wear (longer lifetime) but it also guarantees that, as long as the coating is applied, the performance of the camshaft is consistent (no gradual deterioration in performance).

On the other hand, the emissions outlets suffer because the natural by-product of combustion are carbon deposits. As small, super hard particulates flow through the filters, they come in contact with the moving parts and gouge them in a significant manner [13].

If these parts are harder than the particulates, they are crushed and absorbed; DLC coatings are usually stronger than whatever goes into the engine [15].

2. Theoretical background on DLC coatings

In terms of *Diamond-like carbon properties*, it is often believed that the presence of sp^3 sites is the only criterion for diamond-like properties. This is the source of much confusion. Many soft transparent polymers contain high sp^3 concentrations, but are obviously not considered as diamond-like [4]. In that case, only the optical gap is similar to that of diamond. In pure diamond, all carbon atoms reside in sp^3 sites, but the important point is that these sites are interlinked by strong covalent bonds (about 7.02 eV), with no weak chain element (except at a few crystalline point defects).

This is one of the explanations for diamond's hardness.

In polymers, most of the chains of covalent bonds are terminated by H atoms (C–H covalent bonds have energies of 4.1 eV for H–C sp^3, 4.5 eV for H–C sp^2, and 5.4 eV for H–C sp^1). Between the chain elements, discontinuities of much lower binding energy are produced (hydrogen bonds of a different kind than H–C covalent bonds, and van der Waals bonds).

This explains their “plastic” properties. In graphite, the carbon atoms reside in sp^2 sites, and are interlinked by a higher binding energy of 7.03 eV within the dense plane only, and the fourth electron of the outer carbon atom electron orbital contributes to a weak binding energy of 0.86 eV between planes, explaining why it is much softer, and somewhat brittle.

An amorphous mixture of exclusively carbon atoms will correspond mostly to sp^3 and sp^2 sites (with a few sp^1 sites), and the local binding energies will be distributed around the energies of 7.02, 7.03 and 0.86 eV (often reported with an average of 3.6 eV) [4].

According to the literature, many different categories of DLC films have been reported. S. Neuville presents a very professional synthesis of these in [4]. According to this, the main groups are a-C (non-hydrogenated amorphous carbon), a-C:H (hydrogenated amorphous carbon) and polymeric a-C:H (highly hydrogenated amorphous carbon). Within this classification, the concentration of sp^3 sites should also be considered. However, as we have seen above, the sp^3 concentration alone is not a sufficient criterion by which to determine property differences among different amorphous carbon types, which may have a similar concentration of sp^3 sites. In practice, the mechanical and physical properties are the factors, which define and differentiate DLCs.

- Polymeric amorphous carbon. a-C:H type DLCs containing more than 40 at.% hydrogen, are usually called polymeric amorphous carbon materials [4, 5], which are very similar to “plastic” polymers.
- Soft graphitic a-C:Hs and a-Cs. Amorphous carbon films with a majority of sp^2 sites (>90 at.%) have properties close to graphite and a hardness which can be lower than 10 GPa [4, 5, 6].
- Hard a-C:H and ta-C. Hydrogenated amorphous carbon (a-C:H) can reach high hardness (about 50 GPa) when the H content is not higher than 20 at.% and they contain a high sp^3/sp^2 site ratio [5, 7]. These films have been considered for a long time as very promising because of their low friction coefficient (e.g., against stainless steel) in some inert atmospheres [4, 8, 9].
- Tetrahedral amorphous carbon and polycrystalline diamond. The differentiation between the previously described hard a-C and ta-C can be very subjective when the carbon sp^3 sites are rarely bonded to other types of atoms and carbon sites, with a low bonding energy. In this case, it is no longer necessary to consider the difference between strongly bonded sp^3 and weakly bonded sp^3, since strong bonds (explaining their hardness as already discussed) interlink almost all of them. This is practically the only case where the diamond-like properties can be described with the sole criterion of the sp^3 concentration. Tetrahedral amorphous carbon (ta-C) films contain a majority of interconnected sp^3 sites (50 to 100% with hardness of 70 GPa up to 100 GPa, which is close to diamond) [4, 10]. Polycrystalline diamond is composed of crystallites containing nearly 100% sp^3. They have hardness close to bulk diamond.

According to S. Neuville at al., *ta-C films* are able to support higher levels of stress, in an elastic state, without fatigue effects leading to material failure. This is because the yield stress is higher than conventional DLCs; this benefit is only of value as long as the coating can accommodate the substrate deformation without debonding and as long as no cohesive cracking or delamination of the coating or substrate occurs, (e.g., when the surface is subjected to the Hertzian contact pressures and shearing forces usually encountered in practical contacts) [4].

When the substrate material deforms, then the stress distribution is modified at the coating–substrate interface and in the film material.

For this reason, different research programs tried to find solutions for decreasing gradient of properties between surface (DLC layer) and substrate and design properly the whole system: substrate – interface – film (figure 1). Table 1 presents 2 solutions founded by Bosch, in the case of DLC coatings deposited on certain fuel injection parts [1].

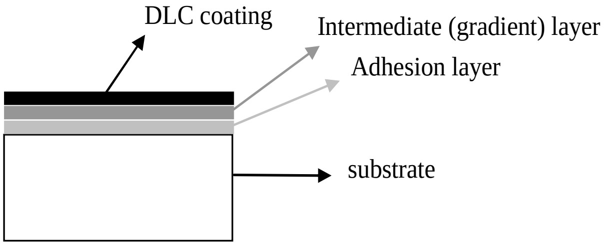


Figure 1. Schematic arrangement of a DLC superficial system with gradient of properties

Table 1. Substrate improving variants of load capacity of DLC coatings [1]

System	A.	B.
Functional layer	DLC (free of metal)	DLC (free of metal)
Intermediate layer	C layer/WC/Cr	CrC
Adhesion layer	Chromium	Chromium
Substrate	Steel	Steel

The tribological properties of DLC coatings do not depend only on the type of coating, but also on working conditions or contact parameters. Because of that coefficient of friction depends on the coating’s thermal stability, which is subject to their, as well as on atmosphere in which coating is operating.

One very important factor in DLC coatings performance is also humidity and the type of gas in which coating is operating [11].

According to M. Sedlakek at al., doping of DLC coating with different metals (Ti, Nb, Ta, Cr, Mo, W, Ru, Fe, Co, Ni, Al, Cu and Ag) leads to changes in their mechanical properties (lower internal stress and hardness, improved adhesion) as well as in their tribological properties, which mainly reflect in decrease of atmosphere dependence [11].

Several methods have been developed for producing diamond-like carbon films.

Plasma Enhanced (assisted) CVD techniques (PECVD) employing RF and DC glow discharges in hydrocarbon gas mixtures produce smooth amorphous carbon and hydrocarbon films (onto substrates negatively biased), which have mixed sp^2 and sp^3 bonds. The CVD processes will generally require deposition temperatures of at least 600°C to give the required combination of properties; however, low temperature deposition is possible. The CVD technique gives good deposition rates and very uniform coatings, and is suited to very large-scale production. *High-power pulsed-DC* sources may use as an alternative of r.f. PECVD method. Pulsed-DC PECVD technologies provide higher deposition rates, DLC films with high adherence, and do not require matching networks, resulting in a reduction of production cost.

Another technique for DLC deposition is based on Ion Beam deposition. This has the advantage of being able to deposit high quality coatings at very low temperatures (near room temperature).

The Closed Field Unbalanced Magnetron Sputter Ion Plating Process, is a technique that can readily apply a-C:H films (> 4 µm) to substrates of any shape. The process is based on closed field unbalanced magnetron sputter ion plating, combined with plasma assisted chemical vapour deposition.

The new technique combines the benefits of both plasma CVD and ion beam deposition. The deposition is carried out between 150 and 200°C in a closed field unbalanced magnetron sputter ion plating system.

Different companies (for instance Bosch) have elaborated several proprietary processes to make diamond-like-carbon (DLC) - coatings. [1, 12]. These are combinations of physical vapour deposition (PVD) and plasma-enhanced chemical vapour deposition (PECVD).

The highly ionized plasma, driven by energy from high frequency electromagnetic excitation and a hydro-carbon gas inlet provide the carbon ions, which form the coating. An intense ion bombardment ensures the film quality and an unbalanced magnetron cathode supplies metal ions for the adhesion layer and the metal-containing films.

3. DLC coatings used for fuel injection system parts

Analysing the technical results in this field, we can see that many internal combustion engines, whether compression ignition or spark ignition engines, use fuel injection systems to provide precise and reliable fuel delivery into the engine combustion chambers.

Such precision and reliability are needed to improve fuel efficiency, maximize power output, and reduce undesirable emissions. Generally, fuel injection systems will include a fuel pump and one or more fuel injectors [16, 17, 18].

The fuel pump supplies fuel to the injectors, which subsequently provide precise control of the fuel supply and timing to engine cylinders [16].

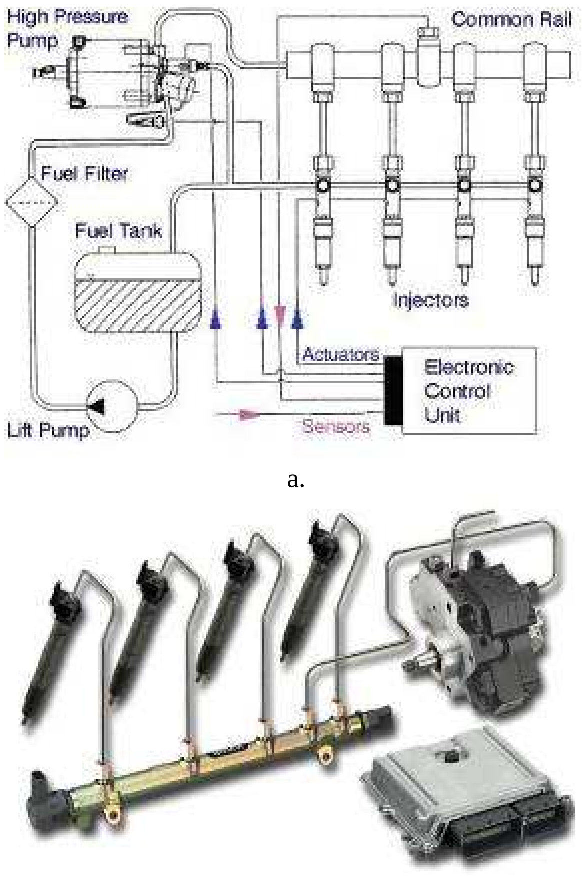
According to the literature, Diesel engines have historically used various forms of fuel injection. Two common types include the *unit injection system* and the *distributor/inline pump* system. While these older systems provided accurate fuel quantity and injection timing control, they were limited by several factors [17].

The common rail injector system is used in gasoline direct injection for modern two and four-stroke gasoline-run engines, but is more popularly used in diesel engines; in gasoline engines, the gasoline is pressurized and injected into the combustion chamber in each cylinder by the common rail fuel line. In diesel engines, the high-pressure fuel rail line feeds individual solenoid valves (figure 2) [17, 18].

Newer common rail diesel systems now use piezoelectric injectors (injectors that can generate an electric field when mechanical stress is applied to them) which results in increased precision and higher pressure.

Figure 3 shows two examples of parts which are coated with DLC [1]. There is the Common-Rail-High-Pressure-Pump, in which a polygon-shaped roller on an eccentric tappet drives the three pistons of the pump. The supporting areas of the roller have to withstand a high load, which is perpendicular to the surface [1]. They need a protection for the running-in process and for the smooth operation during lifetime.

The injector needle opens and closes the outlet of the valve. It has to move very precisely within the valve and needs a coating with a low friction coefficient to guarantee a reproducible amount of fuel per each individual cycle of the engine. These two examples represent the two reasons for using DLC-coatings for high wear resistance and low friction.



a.

b.

Figure 2. Schematic arrangement of a common rail fuel injection system (a) and a photo of it (b)

a.

b.

Figure 3. Parts coated with DLC films inside of a common rail fuel injection system [1]
(a) injector needle; (b) polygon-shaped roller

4. Economic aspects and technical advantages of DLC coatings

The cost of DLC coating depends on, among other things, the size of the part to be coated.

According to Mark Boghe [13] (Bekaert DLC coatings), generally, it could be estimate the cost of the coating to be approximately 30% of the cost of the component. The main advantage of the coating is that it immediately extends the lifetime of the component. You can use it longer and it will wear less. In general, the lifetime is increased by a minimum of 50 per cent. This means that an investment of 30 per cent is offset by an immediate 50 per cent gain – not a bad deal, especially in the current climate.

Another use for DLC coatings is to refurbish components [13]. According to Michael De Maegt, the General Manager of Bekaert DLC, by refurbishment it is possible to taking back coated and used components and recoating them [13]. This way, there is no need to buy a new component. In day-to-day use, most engines do not suffer any excessive wear.

At the same time [13], DLC coatings still have an important role to play as they allow a reduction in friction losses and therefore consumption. According to [13], a good example is coating tappets in small gasoline cars. By coating the tappets, the friction losses are reduced by no less than 40 per cent, which translates into a reduction in fuel consumption of around 1 to 2 per cent.

An application where this technology is focussed at present is in the area of friction reduction, mainly in the valve train assembly and components.

By considering the energy that is wasted through friction, the friction reducing DLC coatings will contribute to a more efficient engine, thereby decreasing emissions.

Preventing wear-related damage to biodiesel driven engine parts is currently a high profile issue in the automotive industry, along with efforts to reduce fuel consumption [14].

Thereby protecting the part by reducing the friction, it is also possible to reduce the wear impact on the parts and their counterparts as well.

In addition, DLC coatings are very inert which means that they do not react with the counterpart as the coating forms an amorphous carbon layer on the surface of the component. The DLC coating also has no affinity with the counterpart thereby eliminating the tendency of seizing or welding when one rubs the surfaces of two similar materials together under pressure. One of the biggest advantages in the application of DLC coatings to valve train components is that this technology can be introduced without changing anything in their logistics or vehicle assembly process [15].

Manufacturers can use the same engine design and install a coated component instead of an uncoated component.

According to Mark Boghe [13] investing in DLC coatings essentially buys you two major benefits. First, the hard and low friction layer will improve the wear resistance of the component. This results in a considerably longer life for your engine and its parts, and a stable performance for the lifetime of the coated component.

5. Future research objectives of the group

Having in mind this theoretical study, the authors will try in the proximity future to find new solutions for developing carbon-based coatings (including here also DLC types), with performing mechanical and tribological properties, which can be prepared at low temperatures, in good efficiency conditions.

6. Conclusions

DLC films may possess exceptional mechanical (high hardness), optical (high optical band gap), electrical (high electrical resistivity), chemical (inert) and tribological (low friction and wear coefficient) properties and can be deposited at low temperature (< 200°C).

The DLC-coatings could be considered an enabling solution for high-pressure fuel injection systems, for components with higher performance and higher lifetime and for cost efficient solutions.

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