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Wear behaviour of hydrogenated DLC in a pin-on-disc model test under lubrication with different diesel fuel types

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ABSTRACT

The wear behaviour of hydrogenated diamond like-carbon (DLC) coating in DLC/steel tribological contact in a pin-on-disc model test under lubrication with two diesel fuels is presented in this work. The first diesel fuel was standard EN590 that contained ester-based antiwear additives. In contrast to EN590, the second diesel fuel, called GDK650, did not contain antiwear additives. It was experimentally observed that the antiwear additives are detrimental to the DLC. The effects of load, speed and temperature on the DLC and steel counterbody wear were investigated. Steel counterbody wear volume was found to be not affected by pressure, temperature, speed and lubricant, whereas the DLC-coating revealed correlation between the parameters and wear rate. Regarding the results of the tribological tests under both diesel lubrications, new mathematical wear laws were developed.

1. Introduction

Diesel engines are increasingly used in passenger cars due to their high efficiency and performance. Modern diesel engines use an injection system, which consists of a high pressure pump, a pressure storage (common-rail) and a set of injectors. A gear pump is used as pre-feed for the fuel supply to the high pressure pump. These systems including gear pump allow injecting the diesel fuel, compressed up to 2000 bar (and even more in the future), into the combustion chamber of the diesel engine in order to increase the specific engine power. Simultaneously, fuel consumption and greenhouse gases are reduced [1]. However, a direct consequence of this high pressure is the high contact pressure and temperature at different tribological contacts involved in the diesel injection systems.

In diesel injection systems, diesel fuel is not only used as combustion fuel, but also as a lubricant. Diesel fuel has become poorer in terms of antiwear elements such as sulfur and aromatic contents. Therefore, the lubricating properties of diesel fuel have drastically decreased [2–4]. Decreasing diesel fuel lubricating properties, combined with increasing contact pressure and temperature, can lead to adhesive wear in, e.g., steel/steel tribological systems, which can – in worst cases – result in component failure. An option to solve this problem in these critical tribological contacts in diesel injection systems is the application of coatings, which reduce wear and at the same time extend the lifetime of the entire injection system.

Diamond-like carbon coatings (DLC) are the most widely used coatings in diesel injection systems, as they combine favourable mechanical and tribological properties. They also provide high wear resistance of the interacting parts in any tribological contact [5–10]. Donnet et al. reported the DLC coating to prolong the lifetime of DLC/steel tribological contacts from two up to five times, as compared to those of steel/steel under the same test conditions [8]. This justifies the use of DLC/steel tribological contact in critical tribological systems in diesel injection systems. As future applications in these systems will lead to even higher surface loads, it is essential to understand the DLC load limits and wear rates in the different tribological systems under multiple stress conditions. The tribological system gear front surface/housing in gear pump is observed under certain conditions to undergo wear in the field and is addressed in this work. Multiple stress conditions in this tribological system consist of combinations of high pressure, temperature, tangential speed of the components in mechanical contact.

Furthermore, the effect of diesel fuel type on the DLC coating is also of interest in this work. Different researches devoted to the effects of lubricating oils on the friction behaviours of DLC coatings have been published. Sugimoto et al. reported a high wear rate of hydrogenated DLC under molybdenum dithio-carbonate (MoDTC)—containing oil in cylinder-on-plate tribotester [11]. Vengudusamy et al. mentioned the formation of a layer protective film on the DLC when lubricated with Zinc dithiophosphate (ZnDTP)-containing oil in ball-on-disc tribometer [12]. The formation of this film

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on DLC under zinc dialkyl dithio phosphate (ZDDP) and molybdenum dialkyl dithio carbamate (MoDTC) containing additives was confirmed by Morina et al. [13]. The effects of ZnDTP and MoDTC and other friction modifiers on the tiboogical behaviours of different DLC coatings are summarized in [14]. The presence of these friction modifiers considerably influences the friction and wear of DLC coatings. It is to point out however that e.g., MoDTC and ZnDTP are not present in standard diesel fuel that is used as lubricant in the present work.

With a view to investigating the DLC wear behaviour as a function of these multiple stress conditions of the gear front surface/housing tribological system, a model test is more appropriate, as it allows studying the effect of important parameters on the DLC wear rate. The diesel lubricated pin-on-disc model test was chosen because of its similarities with the gear front surface/housing tribological system.

2. Experimental setup

2.1. Gear front surface/housing tribological system

The gear pump consists of two separate and rotating gears with inter-meshing teeth as displayed in Fig. 1. In diesel injection systems, the driving gear mounted on the shaft is driven by the chain or belt drive of the combustion engine. This driving gear engages the driven one. Diesel fuel on the inlet side flows into the pump and is trapped between the rotating gear teeth. This action forces the diesel fuel to be carried around the outside of the gears, into the outlet side of the pump. Since the diesel cannot seep back along the path it came, it exits through the outlet port. The tight internal clearances along with the gear rotational speed effectively prevent the fluid from leaking backwards. In the gear front surface/housing tribological system that is addressed in this work, the mechanical clearances between the gear front surface and housing are very tight. The combination of external and internal hydraulic forces acting on the gear imply a given area of gear housing to be in permanent contact with the gear front surface. This area, that is of interest in this work, corresponds to a flat/flat tribological contact. An intolerable gap between both parts that might arise due to wear would result in the dysfunction of the gear pump. Therefore, it is important to prevent wear at the gear front surface/housing tribological system. Depending on the pump, the gear housing can be a DLC-coated 100Cr6 steel. The gear front surface is then an uncoated 100Cr6 steel. The wear in this tribological system is assumed to be impacted by contact pressure p, temperature T and tangential speed v.

2.2. The pin-on-disc model test

The model test reproducing the contact sequence of the gear front surface/housing tribological system in the gear pump was chosen to be a pin-on-disc model test because of the similarities regarding the motion form and contact sequence. Furthermore, the real flat/flat tribological contact of gear front surface/housing is also achieved in this model test. With respect to the gear front surface/housing tribological contact, the pin (equivalent to the housing) was a DLC-coated 100Cr6 steel, whereas the disc (equivalent to the gear front surface) was uncoated 100Cr6. Pressure p, temperature T and tangential speed v were set as test parameters.

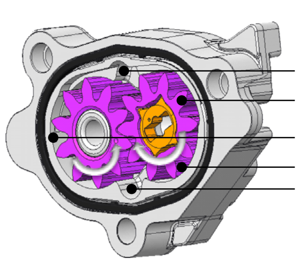

Fig. 1. Overview of gear front surface face/housing tribological system.

2.3. Setting of test parameters

The maximum temperature in the gear front surface/housing tribological system in the field is generally found to be close to 90 °C. In extreme hard operating conditions, it can reach 120 °C. Therefore, the system can be taken to be operated from room temperature until this maximum temperature. Since the room temperature itself fluctuates around T=28 °C, it was of interest to set the minimum manageable temperature slightly higher than that of the room. This minimum value was set to be equal to T=40 °C. The wide temperature range from T=40 °C to 120 °C necessitated the consideration of an intermediate value of T=80 °C. These temperatures were measured during the course of the test by means of thermocouple. Consideration of the experimental setup (SRV tribometer[1], pin and disc geometries) combined with the facility requirement, led to the setting of the maximum and minimum tangential speeds to 0.4 m/s and 1.4 m/s, respectively. The average of these two speeds, 0.9 m/s, was also considered. The maximum and minimum pressures between the pin and the disc in the pin-on-disc model test were set to 40 MPa and 120 MPa, respectively. An intermediate value of 80 MPa was also considered. The pressure at the flat/flat tribological contact pin/disc was obtained by dividing an applied load F in N by the contact area in mm^2. It should be noted that these pressures are considerably higher than those obtained in the gear front surface/housing tribological contact in real applications, which are generally lower than 15 MPa. The advantage of increasing the pressure in model test is to shorten the experiment duration to create measurable wear. This procedure has to be done carefully not to stimulate unrealistic wear mechanisms by exaggerated pressures.

Two diesel fuels were used as lubricants: The standard diesel fuel EN590 (according to DIN EN 590) and a special diesel blend called "GrenzDieselKraftstoff" GDK650. EN590 contained ester-based antiwear additives and was free of biodiesel components, whereas GDK650 did not contain any antiwear additives. Both fuels also differed from each other in their respective lubricating properties. The high frequency reciprocating test rig (HFFR[2]) values of EN590 and GDK650 fuels are 430 μm and 650 μm, respectively.

2.4. Design of experiment

In view of achieving experimental results in a reasonable time, it was useful to use a Design of Experiment (DoE). The used DoE in this work is the D-optimal and has the advantage of requiring the smallest possible number of test runs, while at the same time giving access to the wear dependence on test parameters. The working principle of D-optimal designs consists in the finding of the minimal test runs necessary to compute the optimal of the determinant of a design matrix. The design matrix elements consist of given values of the test parameters to be investigated. The design matrix element number depends on the set model (linear, quadratic and cubic) describing the response dependence on the predictors. The design matrix is generated by using the set model to expand the setting for every factor in every test run.

[1] A product of Optimol Instruments Prüftechnik GmbH.
[2] See ASTM D6079 guideline for details.