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Minimizing Frictional Losses in Crankshaft Bearings of Automobile Powertrain by Diamond-like Carbon Coatings under Elasto-hydrodynamic Lubrication

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ABSTRACT

An efficient powertrain technology contributes to sustainable lowering of greenhouse gas emissions in terms of reducing mechanical losses and saving fossil fuels. Minimization of frictional losses of highly loaded components in automobile powertrain as crankshaft plain bearings and gears offers massive potential for target achievement. Application-related investigations of diamond-like carbon (DLC) coatings ZrC_g (a:C-H/ZrC_g) and nanocomposite (nc)-ZrC (a-C:H/ZrC) in lubricated rolling-sliding contacts in twin-disc and gear efficiency test-rig revealed great potential of ZrC_g for efficiency improvement in automobile gearboxes by reducing mechanical losses up to 39 % under elasto-hydrodynamic lubrication (EHL) compared to uncoated gears. With regard to plain bearings, ZrC_g and nc-ZrC coated modified prototype bearings exhibited a friction advantage of up to 36 % in EHL compared to standard bearings in an engine test bench. This yet largely unknown favorable effect of DLC coatings under rolling-sliding conditions in EHL opening doors to new possibilities in tribology and efficiency improvement was attributed to the thermophysical properties of DLC coatings and was confirmed by simulations of rolling-sliding contacts.

1. Introduction

Increasing awareness of the impact of climate change promotes the political will to reduce greenhouse gas emissions in the European Union resulting in stricter CO_2 emission standards for automotive manufacturers. In terms of fuel energy dissipation of automobiles, the largest portion of fuel energy losses can be attributed to exhaust (33 %) and cooling (29 %) whereas besides losses due to the air resistance of automobiles (5 %) frictional losses in combustion engine, gearbox, tire-road contact and brakes contribute to fuel energy losses with 33 % [1]. Therefore, minimization of frictional losses in highly loaded rolling-sliding contacts of automobile powertrain is a promising approach to improve efficiency, save fossil fuels and reduce greenhouse gas emissions [2–4]. The internal combustion engine and in particular, the piston and cranktrain assembly contributing to frictional losses between 40 % and 45 % come into focus of R&D in terms of efficiency improvement [1, 5–8]. Here, the plain bearings are of high interest since their share of frictional losses can be found between 15 % and 25 % [5,7,9,10].

Plain bearings designed as two-material or as three-material bearings can be considered state-of-the-art in modern engine technology. Whereas two-material bearings typically consisting of a roll clad aluminum functional surface on a steel backing are used in gasoline and naturally aspirated diesel engines under low or medium loads, three-material bearings composed of a sputtered or electrochemical modified slide layer, a barrier layer and a bronze or copper based bearing layer directly being cast or sintered to the steel backing are predominantly used in engines subjected to higher loads, e.g. large piston pin bushings, main bearings and crankshaft bearings. Increasing power densities in current engine development due to highly charged engines accompanied by the growing trend towards “downsizing” and the series application of start/stop-systems place high demands on plain bearings in terms of loading capacity and friction behavior. In particular, the required loading capacity can be found in direct contradiction to the demands of soft surfaces related to the capability of plain bearings to embed hard particles in order to avoid damages on plain bearings and crankshaft (soft/hard contact). Thus, the aim of this work was to increase bearing loading capacity up to p = 150 MPa and to reduce frictional losses in plain bearings of automobile crankshaft train by means of geometrically modified bearing shells and the application of diamond-like carbon (DLC) coatings. The application of diamond-like carbon (DLC) coatings on components of

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automobile powertrain, e.g. piston rings, tappets, camshafts and plungers deposited by means of physical vapor deposition (PVD) and plasma enhanced chemical vapor deposition (PECVD) can be considered a common approach to meet the challenges of friction reduction, wear protection and efficiency improvement, in particular, under dry-running or boundary and mixed lubricated tribological systems [11–24]. In this work, the metal and hydrogen containing DLC coatings graded zirconium carbide (a-C:H/ZrC_g) and nanocomposite a-C:H/nc-ZrC of IOT were deposited on prototype plain bearings and crankshaft to ensure a hard/hard contact. The components were tested in a 4-cylinder in-line-engine test bench at Institute of Combustion Engines (VKA) of RWTH Aachen University. The DLC coatings ZrC_g and nc-ZrC already demonstrated their high potential for reducing friction of highly loaded rolling-sliding contacts under application-related conditions in automobile gearboxes as reported in [25]. Tribological test series performed in the gear efficiency test-rig at Gear Research Center (FZG) of TU München using ZrC_g and nc-ZrC coated gears revealed a friction reduction of 15 % for small circumferential speeds in boundary friction and up to 39 % at higher circumferential gear speeds at fully separated surfaces under elasto-hydrodynamic lubrication (EHL conditions) in the fluid friction regime compared to uncoated steel gears. The favorable friction behavior was attributed to the thermophysical properties of the DLC coatings which have an impact on viscosity and shear resistance of the lubricant. In addition to testing the DLC coatings ZrC_g and nc-ZrC, the influence of geometrically modified prototype bearing shells, i.e. optimized roundness, elimination of chamfers and greater clearance on the friction behavior was tested in engine test bench of VKA.

2. Experimental details

2.1. Coating deposition

Heat-treatable steel 42CrMo4 (AISI 4137) was chosen for manufacturing of standard and prototype bearing shells as well as of the crankshaft since this material finds widespread application in automobile cranktrain. In order to ensure a sufficient load carrying capacity for the deposition of DLC coatings [26,27] in combination with a corrosion protection against corrosive engine oils [28–30], the bearings and crankshafts were quenched and tempered (QT) followed by plasma nitriding (P) to set a surface hardness of $H = 820\ HV_{0.3}$ for 42CrMo4 QTP). Standard bearing shells of w = 20.0 mm width and two different types of DLC coated prototype bearing shells of w = 20.0 mm and w = 16.5 mm width were tested in this work. The DLC coated prototype bearing shells of width w = 20.0 mm will be referred to as MOD-1 for the DLC coating a-C:H/ZrC_g (ZrC_g) and MOD-2 for the DLC coating a-C:H/nc-ZrC (nc-ZrC), respectively. The DLC coating plain bearing shells with reduced width w = 16.5 mm are identified by MOD-2 for ZrC_g and by MOD-4 (nc-ZrC). Whereas the size and position of supply bore holes and slots were kept identical for standard and prototype bearing shells, the prototype bearing exhibited slight geometrical variations, i.e. optimized roundness, elimination of chamfers and greater clearance as listed in Table 1.

The measurements of a standard bearing (a) and a prototype bearing (b) in mounted conditions at room temperature can be taken from Fig. 1. The absolute diameters are given in Fig. 1 due to different scales for illustration of the bearing shells. The optimized roundness of the prototype bearing shells as listed in Table 1 becomes apparent in Fig. 1 b). The optimized roundness (55.045 mm • 55.012 mm) led to a reduced flow cross section of the prototype bearing despite the minimum bearing clearance (c = 0.83 ‰) was higher compared to the standard bearing (c = 0.4 ‰, see Table 1). Particularly in the parting line, comparably high flow cross sections was found for the standard bearing which were significantly reduced due to the design of the prototype bearings.

Table 1
Data of standard steel and prototype plain bearings for engine test bench trials.

Properties	Standard bearing shell	Prototype bearing shell
Material	42CrMo4 QTP	42CrMo4 QTP
Width [mm]	20.0	20.0; 16.5
Geometry [mm]	55.072 • 54.978	55.045 • 55.012
Clearance [‰]	0.4	0.83
Chamfer & positioning lug	Yes	No

The two metal and hydrogen containing diamond-like carbon (DLC) coatings a-C:H/ZrC_g (ZrC_g) and a-C:H/nc-ZrC (nc-ZrC) were deposited at IOT in an industrial scale coating unit CC800/9 Custom from CemeCon AG, Wuerselen, Germany. The coating unit was equipped with two direct current (dc) magnetron sputtering (MS) cathodes operating in middle frequency (mf) pulsed mode. For deposition of the DLC coatings, two zirconium targets with a purity >99.5 % were used. Argon (Ar) and acetylene (C_2H_2) served as process and reactive gas. Details about the deposition process and the process parameters can be found in [25]. At the end of the heating phase, an in-situ plasma etching process was started to activate the substrate surface in order to ensure a sufficient adhesion between the coatings and the bearing shells [16]. Besides the plain bearing shells, a set of fourteen zirconium carbide based coatings was deposited on cemented carbide (WC/Co, THM12) at varying reactive gas flux (C_2H_2) between minimum and maximum within the process window of ZrC_g. The coatings were used for the characterization of structure, morphology, chemical composition and phase composition by means of high resolution transmission electron microscopy (HRTEM), scanning electron microscopy (SEM), glow discharge optical emission spectroscopy (GDOES) and X-ray diffractometry (XRD).

2.2. Coating characterization

Coating morphology and thickness was evaluated by means of scanning electron microscope (SEM) ZEISS DSM 982 Gemini, Jena, Germany, micrographs of fractured cross section using a secondary electron (SE) detector. A transmission electron microscope (TEM) FEI Tecnai F20, Hillsboro, OR, USA, was used to analyze two ZrC based DLC coatings deposited at constant reactive gas flux. For this purpose the coatings were prepared by means of focused ion beam (FIB). Phase analysis was carried out via high angle (HA) X-ray diffraction (XRD) using grazing incidence (GI) X-ray diffractometer XRD 3003, General Electric, Munich, Germany. Analysis was done using Cu-Kα radiation (λ = 0.15406 nm) operated at U = 40 kV and I = 40mA using the following parameters: GI: ω = 3°; diffraction angle 2θ: 20° to 80°; step width: s = 0.05°; step time: t = 10 s. High quality (star) JCPDS cards 00-035-0784 (ZrC), 00-025-1047 (WC) and 01-078-2921 (Zr) were used for peak identification and phase analysis. The chemical composition (zirconium share x_{Zr}) of the ZrC based DLC coatings deposited at constant reactive gas flux was analyzed by glow discharge optical emission spectroscopy (GDOES) in radio frequency (rf) mode as a function of etching time. A GDOES Profiler type JY 5000 RF, Horiba Jobin Yvon, Japan, equipped with an anode of 4 mm was used. Mechanical properties, universal hardness HU, and modulus of indentation E_{IT}, of the DLC coatings were determined using the method of nanoindentation. A Nanoindenter XP by MTS Nano Instruments, Oak Ridge, TN, USA, was applied for this purpose. The indentation depth did not exceed 1/10 of the coating thickness. The evaluation of the measured results was based on the equations according to Oliver and Pharr [31]. In accordance with [32–35] a Poisson's ratio $\nu = 0.25$ was assumed for the DLC coatings. Adhesion of the compounds was evaluated by Rockwell indentation tests with a load of 1,471 N (HRC) investigating the indents by means of light microscopy Keyence VHX-100, Neu-Isenburg, Germany. According to VDI guideline 3198 adhesion was analyzed distinguishing between different adhesion classes (HF) from HF 1 (very good adhesion) to HF 6 (insufficient adhesion). Scratch tests according to ISO 20502 were performed to quantify adhesion by determining critical scratch load L_{C2}.