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Influence of wetting and thermophysical properties of diamond-like carbon coatings on the frictional behavior in automobile gearboxes under elasto-hydrodynamic lubrication

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ABSTRACT

With regard to the transportation sector, an efficient powertrain technology contributes to sustainable lowering of CO_2 emissions. Due to the periodic or continuous operation in boundary and mixed friction, minimization of friction losses in automobile gearboxes offers massive potential in terms of efficiency improvement and saving fossil fuels. In close cooperation between the Surface Engineering Institute (IOT) and the Gear Research Center (FZG), the aim of this work was to reduce friction losses in powertrain by diamond-like carbon (DLC) coatings on highly loaded gears under severe rolling–sliding conditions. The zirconium based DLC coatings ZrC_g (a:C-H/ZrC_g) and nanocomposite ZrC (a-C:H/ZrC) were deposited by physical vapor deposition (PVD) at IOT. The industrial DLC coating DLC-REF1 served as reference. Application-related tribological tests of lubricated highly-loaded rolling–sliding contacts were performed in a twin-disc test-rig and a gear efficiency test-rig at FZG. Calculations and measurements of relative lubricant film thickness confirmed that the tribological model tests covered the entire friction regime from boundary and mixed friction to fluid friction (elasto-hydrodynamic lubrication, EHL). Despite complete separation of the coated surfaces, the Coefficient of Friction was reduced by 35% using ZrC_g coated discs in the twin-disc test-rig. Practical investigations of DLC coated gears in the FZG gear efficiency test-rig revealed that compared to uncoated gears friction losses in EHL were reduced by up to 25% using the industrial reference DLC-REF1 and 39% using ZrC_g, especially at higher loads and higher circumferential speeds. This yet widely unknown favorable effect of DLC coatings under EHL conditions was attributed to the thermophysical properties of DLC coatings and confirmed by simulations of real rolling–sliding contacts at FZG. Wetting analyses of tribological surfaces were analyzed determining the surface properties, interfacial tension and surface energy, of the DLC coatings and the gear oils by means of contact angle measurements. The adhesion energy was calculated from contact angle data. Correlation analyses revealed a clear impact of the interfacial tension and adhesion energy on the frictional behavior under boundary and fluid friction conditions. It was found that a higher adhesion energy (good wetting) contributes to a lower CoF under boundary and mixed friction conditions as well as in the fluid friction regime (EHL).

1. Introduction

Increasing awareness of the impact of climate change promotes the political will to reduce greenhouse gas emissions in the European Union. Minimization of frictional losses in highly-loaded rolling–sliding contacts of automobile gearboxes is a promising approach to improve efficiency, save fossil fuels and reduce greenhouse gas emissions [1–3]. Against this background, surface properties of lubricated rolling–sliding contact partners periodically or continuously operating under boundary and mixed friction conditions and the interactions with the lubricant can be considered as the key factors influencing the friction behavior. The application of diamond-like carbon (DLC) coatings on machine elements deposited by means of physical vapor deposition (PVD) and plasma enhanced chemical vapor deposition (PECVD) is a common approach to meet the challenges of friction reduction, efficiency improvement and wear protection in various tribological systems [4–11]. This particularly includes piston rings, tappets, camshafts and plungers of injection systems and gearboxes [2,9–15]. With regard to highly loaded rolling–sliding contacts as gears and rolling bearings, DLC coatings contribute to wear reduction due to their favorable effect on the load capacity in terms of pitting, scuffing and micro-pitting [4–7]. Due to their properties in terms of friction reduction and wear

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protection, DLC coatings are typically used in dry-running or under boundary and mixed friction conditions [4,5,7,8,11,16–22]. But application of these coatings in the fluid friction regime comes into focus of research and development.

With regard to lubricated tribological systems, interactions between the tribological surface of machine elements and the lubricants play a key role in terms of friction and wear behavior [23–26]. Industrially used and commercially available lubricants are usually mineral oils formulated with complex additive packages, i.e. anti-wear (AW)/extreme-pressure (EP) additives to meet the demanding requirements of highly loaded tribological systems. Therefore, the lubricants have been modified within the past decades to ensure optimum wetting properties on steel surfaces to contribute to friction reduction and wear protection [24,25]. The tribological performance is controlled by the formation of tribochemical films based on tribochemical reactions between metallic surfaces and additive molecules. Here, the formation of sulfides from FM-additives and phosphates from AW-additives contributes to friction reduction and wear protection, respectively [27,28]. However, since DLC coatings are increasingly gaining attention in various highly loaded and lubricated tribological systems [29], the chemical composition of the tribological surfaces changes and the basic chemico-physical interactions between the steel surface and the formulated lubricants cannot be transferred directly to the DLC coated tribological system [8,25]. Here, the low reactivity [30,31] or chemical inertness [8] of DLC coatings can be considered the main difference to steel surfaces which limit the tribochemical interactions with lubricants and additive packages [32]. However, efficiency improvement in automobile powertrain in terms of frictional losses, fuel consumption, loading capacity and reduced greenhouse gas emissions requires adequate tribological performance of DLC coated machine elements under oil-lubricated conditions, using oil/additive packages originally developed for uncoated steel surfaces [24,33]. In particular in the transition from boundary to mixed friction conditions where solid asperity interactions do not longer prevail, physical interactions between solid surface (DLC) and the fluid phase (lubricant) significantly contribute to the tribological performance. This effect becomes even more pronounced under elasto-hydrodynamic lubrication (EHL) where a complete lubricant film is formed which separates the tribological contacts. Therefore, wetting and the physical interactions between DLC coatings and lubricants, i.e. interfacial tension σ_{sl} and adhesion energy W_{ad} can be considered decisive and need to be investigated [8,25,34–36].

With regard to friction reduction in automobile powertrain, the aim of the close cooperation between Surface Engineering Institute (IOT) of RWTH Aachen University and Gear Research Center (FZG) of Technische Universität München was to investigate the influence of DLC coated tribological surfaces in lubricated highly loaded rolling–sliding contacts. For this purpose, the hydrogen and metal containing DLC coatings graded zirconium carbide (a-C:H/ZrC_g) and nanocomposite a-C:H/nc-ZrC deposited by PVD at IOT and an industrial hydrogen containing DLC coating DLC-REF1 deposited by means of PECVD were tested under high stress. Lubricated tribological model tests with increasing application relevance were performed at IOT and FZG. Aiming at an investigation of the sliding share of friction in point contact in a simplified environment, a pin-on-disc tribometer at IOT was used. In terms of real loading conditions for toothing in gearboxes, slip-afflicted rolling–sliding motion in line contact was analyzed by performing tribological test series in a twin-disc test-rig and a gear efficiency test-rig of FZG using real gears. This procedure ensured a high industrial and application relevance of the tribological analyses. The impact of surface properties, i.e. interfacial tension and adhesion energy, on the frictional behavior was investigated by correlation analyses. For this purpose, the contact angle measurement data using five different types of gear oils and the frictional behavior obtained in the pin-on-disc tribometer and in the twin-disc test-rig were connected to identify correlations between the wetting properties and the Coefficient of Friction (CoF).

2. Experimental details

2.1. Coating deposition

Since the case hardening steel 16MnCr5 (AISI 5115) finds widespread application for manufacturing of gears for automobile and industrial gearboxes, it was chosen as substrate material in this work. Case hardening of the steel samples to a surface hardness of 60 ± 2HRC with a case hardening depth CHD > 1 mm provided for sufficient strength at high stresses and ensured a sufficient carrying capacity for the deposition of DLC coatings as reported in [7,8,26]. The 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 the 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. The process parameters for the deposition of a-C:H/ZrC_g and a-C:H/nc-ZrC can be taken from Table 1. The deposition processes mainly differ in the process design and reactive gas ramps, the dc cathode power as well as the mf bias voltage.

Deposition temperature of the mfMS processes was kept <180 °C to avoid annealing of temperature-sensitive case hardened steel. 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 substrate (round blanks, discs and gears C-PT) for tribological applications [5].

2.2. Coating characterization

Coating morphology and thickness were 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 the graded profile and morphology changes of a-C:H/ZrC_g. For this purpose the coating was prepared by means of focused ion beam (FIB). 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 [37]. In accordance with [38–43] a Poisson's ratio $\nu = 0.25$ was assumed for the metal and hydrogen containing DLC coatings. Surface roughness of the coatings was analyzed by means of confocal laser scanning microscopy, Keyence VK-X210, Tokyo, Japan, according to ISO 4287 (line profile) in order to determine Ra and Rz. Adhesion of the compounds was evaluated by Rockwell indentation tests with a load of 1471 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 loads L_{C1} to L_{C3}.

2.3. Lubricants

Five different lubricant types were chosen for tribological tests in pin-on-disc tribometer and wetting analysis by means of contact angle measurements. Since mineral oil is widely used in gearboxes, MIN100 served as reference. Besides mineral oil, four common synthetic oil types, i.e. polyalphaolefin (PAO), trimethyl propane (TMP) ester, polyether (PE) and polyglycol (PG), increasingly used as lubricants in