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Friction reduction of highly-loaded rolling-sliding contacts by surface modifications under elasto-hydrodynamic lubrication

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ABSTRACT

Due to the operation in mixed and boundary friction, minimization of friction losses in automobile powertrains offers high potential for lowering of greenhouse gas emissions and saving fossil fuels. In cooperation between Surface Engineering Institute (IOT) and Gear Research Center (FZG), surface modifications in terms of stochastic and deterministic structures, diamond-like carbon (DLC) and nitride hard physical vapor deposition (PVD) coatings were tested in lubricated rolling-sliding contacts in twin-disk and gear efficiency test-rig. It was found that deterministic structured surfaces provide for reduction of friction losses by up to 7% under extreme boundary friction conditions at high Hertzian stresses and small relative lubricant film thicknesses. Application-oriented tests using DLC coated gear wheels in gear efficiency test-rig exhibited a reduction of friction losses between 10% and 21% compared to uncoated gear wheels. The DLC coating ZrC_g developed at IOT provided for friction reduction of 15% for small circumferential speeds in boundary friction. Friction losses were reduced by up to 39% at higher circumferential speeds in spite of fully separated surfaces in the fluid friction regime. Due to their thermophysical properties, it is assumed that DLC coatings have an impact on viscosity and shear resistance of the lubricant.

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1. Introduction

Raising awareness of the consequences of climate change and the demand for reduction of greenhouse gas emissions and saving fossil fuels lead to constantly rising demands on efficiency of machines and drive systems [1–6]. In the automotive sector, besides alternative drive concepts, minimization of friction losses in rolling-sliding contacts of automobile gearbox offers significant potential for target achievement in terms of efficiency improvement and reduction of greenhouse gas emissions. Surface properties of rolling contact partners periodically or continuously operating under boundary and mixed friction conditions can be considered one of the main factors influencing the friction behavior. Stochastic surface structures prepared by precision machining are state-of-the-art. Additionally, deterministic structured surfaces are already being used in components under low loaded, lubricated contacts, e.g. plain and thrust bearings [7]. In contrast, the applicability of deterministic structured surfaces on components in highly loaded rolling contacts, i.e. gear wheels in gearboxes, has not been adequately researched. Similar to low loaded tribological contacts, an intelligent design of deterministic surface structures can be considered essential to ensure minimization of friction losses and simultaneously, avoid breakdown of lubricating film resulting in deterioration of friction behavior [8–11]. Comprehensive experimental works and simulation calculations on the influence of deterministic structures on lubricating film formation in the mixed friction area as well as under elasto-hydrodynamic lubrication reveal two crucial criteria for the design of deterministic surfaces [9–12]. This includes the size of the area within which the lubricant film thickness is influenced by a single dimple as a function of dimple geometry (aspect ratio) and operating conditions, as well as the number of contacting dimple.

Another measure to modify frictional components aiming at efficiency improvement of drive systems is the application of diamond-like carbon (DLC) coatings by means of physical vapor deposition (PVD) and plasma enhanced chemical vapor deposition (PECVD) [13–20]. The motivation for using DLC coatings on components in injection systems and gearboxes as well as on piston rings, tappets, camshafts and plungers is based on the favorable friction and wear behavior of DLC coated tribological systems [5,18–24]. Besides reduction of friction losses, DLC coatings contribute to wear reduction and therefore, lead to increasing service life of coated components. Increased service life can be attributed to the favorable effect of DLC coatings on the load capacity (pitting, scuffing and micro-pitting) of components as gear wheels and rolling bearings [13–16]. In addition to DLC coatings, chromium based nitride hard coatings are used to reduce wear in tribological systems [16,25–28].

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Since DLC and nitride hard coatings are typically used in dry-running or under boundary and mixed friction conditions [13,14,16,17,20,25,29–35], application of these coatings in the fluid friction regime comes into focus of research and development.

With regard to friction reduction in automobile power train and identifying loss-optimized combinations of modified component surfaces and lubricants, the aim of the close cooperation between Surface Engineering Institute (IOT) of RWTH Aachen University and Gear Research Center (FZG) of TU Munich was to investigate the influence of modified surfaces by structures and PVD coatings to optimize the friction behavior of highly loaded rolling contacts. This included the preparation of stochastic surface structures by mechanical precision machining and the production of deterministic surface structures by laser machining in order to influence the lubrication conditions in the lubrication gap. Additionally, the hydrogen and metal containing DLC coatings graded zirconium carbide (a-C:H/ZrC_g) and nanocomposite a-C:H/nc-ZrC of IOT and two industrial hydrogen containing DLC coatings DLC-REF1 (a-C:H) and DLC-REF2 (a-C:H) deposited by means of plasma enhanced chemical vapor deposition (PECVD) were tested under high stress in lubricated rolling contacts. Furthermore, the chromium based nitride hard coatings ($Cr_{0.77}Al_{0.23}$)N and nano-structured (ns)-CrN/($Cr_{0.50}Al_{0.50}$)N of IOT were tested since these coatings revealed huge potential for wear protection of highly loaded components in Collaborative Research Center 442 [17,36]. In close cooperation between IOT and FZG, tribological model tests with decreasing degree of abstraction were performed. First, a pin-on-disk (PoD) tribometer was used to analyze the sliding share of friction in point contact in a simplified environment at IOT. With the view to real loading conditions for toothing in gearboxes, slip-afflicted rolling-sliding motion in line contact was investigated by performing tribological tests in twin-disk test-rig and gear efficiency test-rig of FZG using real gear wheels. This procedure ensured a high industrial and application relevance of the tribological analyses.

2. Experimental setup

Because of its relevance for manufacturing of gear wheels for automobile and industrial gearboxes, case hardened steel 16MnCr5 (AISI 5115) was chosen as substrate material to ensure sufficient strength at high stresses and sufficient loading capacity for the deposition of PVD coatings. The influence of lubricated structured surfaces on the friction behavior was evaluated by means of stochastic structured surfaces (precision machining: polishing, transversal, longitudinal and cross grinding, lapping) and deterministic structured surfaces (laser machining) on disks for twin-disk test-rig and gear wheels for gear efficiency test-rig. Surface topography 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. The stochastic structured surface topography was determined by tactile roughness measurements according to DIN EN ISO 3274. Precise measurement of deterministic surface structures was done by white light interferometry. The metal and hydrogen containing carbon based 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, 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. The process parameters for deposition of a-C:H/ZrC_g are listed in Table 1.

Deposition of the chromium based nitride hard coating ($Cr_{0.77}Al_{0.23}$)N at IOT was carried out in an industrial scale coating unit CC800/9 SinOx from CemeCon AG, equipped with four mfMS-cathodes. Four

Table 1
Process parameters for the deposition of ZrC_g (a-C:H/ZrC).

Process parameter	Unit	Value
Time	s	9030
Argon flux, F_{Ar}	sccm	500 mPa (pressure controlled)
Acetylene flux, F_{C2H2}	sccm	10–70 (ramped)
Pressure, p	mPa	500
dc cathode power, P	W	2400–2000 (ramped)
mf bias voltage, U_{bias}	V	35–200 (ramped)
Frequency, f	kHz	250

CrAl20 targets (Cr target with 20 pieces of diameter 15 mm Al plugs (purity: Cr 99.9% and Al 99.5%) were used for the deposition of ($Cr_{0.77}Al_{0.23}$)N. The chromium based nitride hard coating ($Cr_{0.50}Al_{0.50}$) with nanostructured (ns) toplayer CrN was deposited by means of cathodic arc evaporation (CAE). Higher surface roughness of nitride coatings due to droplet emission in CAE processes compared to sputtered PVD coatings [37,38] was exploited to deposit the nanostructured toplayer serving as a lubricant reservoir for friction reduction in highly loaded tribological contacts as described by Bobzin et al. [26] and by Michalczewski et al. [39]. The nitride hard coating ns-CrN/($Cr_{0.50}Al_{0.50}$)N was deposited using a 20″ PVD arc ion plating facility by Sulzer Metaplas, Bergisch-Gladbach, Germany. A process parameter study was carried out to identify the most suitable surface topographies of CrN toplayers ensuring a lubrication supporting function. One Cr target (purity 99.5%) and one Al target (purity 99.5%) on two cathodic arc evaporation sources in a 180° setup were used. Argon (Ar) and nitrogen (N_2) were utilized as process and reactive gas. Deposition temperature of the mfMS and CAE processes was kept <180 °C in order to avoid annealing of temperature-sensitive case-hardened steel AISI 5115. 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 steel substrate (round blanks, disks and gear wheels C-PT) for tribological applications [13]. In order to evaluate coating morphology and thickness, scanning electron microscope (SEM) ZEISS DSM 982 Gemini, Jena, Germany, micrographs of fractured cross section were taken using a secondary electron (SE) detector. Transmission electron microscope (TEM) FEI Tecnai F20, Hillsboro, OR, USA, was used to analyze the structure 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 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 $\frac{1}{10}$ of coating thickness. The evaluation of the measured results was based on the equations according to Oliver and Pharr [40]. In accordance with [41–47], a Poisson's ratio of $\nu=0.25$ for DLC coatings and chromium based nitride coatings was assumed. Rockwell tests according to DIN EN ISO 6508 were performed to prove that no tempering effects in the steel substrate occurred during coating deposition. Adhesion of the compounds was evaluated via Rockwell indentation tests with a load of 1471 N (HRC) investigating the indents by means of light microscopy Keyence VHX-100, Keyence GmbH, Neu-Isenburg, Germany, according to VDI guideline 3198, 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}–L_{C3}.

2.1. Pin-on-disk tribometer

However, highly loaded gear applications are affected by a complex superposition of sliding and rolling friction [48,49] in line contact, tribological tests in Pin-on-Disk (PoD) tribometer under continuous sliding motion in point contact provided for the possibility

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