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# Thermal effects influencing stability and performance of coatings in automotive applications

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ABSTRACT

Carbon based coatings are well established in the automotive industry to solve tribological problems in automotive applications. In systems under high load and/or high contact pressures, these coatings are used to reduce friction and wear. Other coatings like chromium nitride are useful to prevent scuffing. However, a real challenge in evaluating coatings for their suitability in automotive applications is the broad range of conditions which defines the load collective of the tribological system.

In this work, we focused on the thermal effects that might influence the stability and performance of coatings in tribological applications. In a car engine, the temperature range might be much broader than the −20 °C to 120 °C as given by the average oil temperature. In the tribological contact zone the temperature can be higher up to several hundred degrees Celsius, especially if it comes temporary dry running due to starved lubrication. These locally high temperatures can affect the properties of a coated surface, but the coated surface itself might also have an influence on the temperature in the contact zone. This is especially the case, if coatings with low thermal conductivities like carbon based materials are used.

Therefore, we focused our here presented work on the investigation of the influence of the temperature on the wear performance, the friction coefficient and the thermal stability of a DLC coating in unlubricated conditions. The DLC coating was submitted to dry running reciprocating sliding wear tests in a broad temperature range and then the thermal stability of the coating has been analyzed by means of hardness measurements (nanoinentation) and a structural approach (Raman spectroscopy). In addition, we analyzed the effect of a DLC coating on the tribological properties of a lubricated contact on a two-disc tribometer. These efforts were completed by measurements of the thermal conductivity of the DLC coating.



## 1. Introduction

The current legislative restrictions for the automotive industry to improve the efficiency of combustion engines have led to the development of so-called downsized engines. Due to the high power densities in these engines, local contact pressures of rolling or sliding contacts are so high that scuffing is a possible risk for the longtime stability. In addition, the use of low-viscosity oils with reduced wear protection capabilities deteriorates the situation further. Therefore, carbon based coatings like DLC (diamond like carbon) combining low friction against steel and high wear resistance are widely used in the automotive industry to solve tribological problems [1,2].

Most tribological contacts in the power-train of a car are lubricated. However, the use of low-viscosity oils under starved lubrication can lead temporarily to dry running conditions. One of the most important effects under dry running conditions is the transient temperature rise due to frictional heating, commonly called “flash temperature”. It can be assumed that the heat is generated on the contacting surfaces or within the first top few micrometers of the contacting bodies. The heat is then dissipated from the contact zone into the bulk material in a rather short period of time, depending on the properties of the contacting materials. The high flash temperature has to be distinguished from the slow rise of the bulk temperature. This concept has already been described by Blok [3,4] and Jaeger [5]. The flash temperature can be high enough to cause changes in the mechanical and metallurgical properties of sliding surfaces. This is especially critical for the use of DLC coatings. This material is, depending on the pressure, thermally stable up to about 350 °C and graphitizes at higher temperatures. While graphitization limits the application of DLC coatings, it also allows their great running-in properties.

In this work, we investigated the influence of the temperature on the wear performance, the friction coefficient and the thermal stability of a

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DLC coating submitted to a reciprocating ball-on-flat sliding wear test without lubrication. In addition, we analyzed the influence of a DLC coating on the tribological properties of a lubricated contact in a disc-on-disc tribometer by varying the relative speed of the two discs in order to reproduce the Stribeck curve.

## 2. Experimental

### 2.1. Coating deposition

The here investigated DLC coating (Oerlikon Balzers Balinit® DLC Star) is a hydrogenated amorphous carbon coating and was prepared in a commercially available PVD/PACVD coating system (Oerlikon Balzers RS50) with a residual pressure in the range of $2 \cdot 10^{-5}$ mbar or below. The coating chamber was equipped with four magnetron sources, each of them being occupied by a chromium target. The substrates were coated in a 2fold-rotation regime.

Prior to deposition, the steel substrates were heated to approximately 150 °C and etched in a pure Ar plasma. During etching, the ions were extracted from a plasma beam, supported by an electron emitter. After etching, a pure Cr layer of approximately 0.2 μm was deposited by dc-sputtering from the four Cr targets in a pure Ar atmosphere in order to assure a good adherence between the steel substrate and the following coating. After the Cr adhesion layer, a load supporting, hard and ductile CrN layer of approximately 0.5 μm was deposited by operating the four Cr targets in a mixed $Ar/N_2$ gas mixture with a total gas pressure of approximately $3 \cdot 10^{-3}$ mbar. In order to ensure a good adhesion of the following a-C:H coating to the CrN layer, we then deposited a gradient Cr–C layer of approximately 0.7 μm by decreasing the Cr target power and increasing the bias voltage and the $C_2H_2$ flow in a mixed $Ar/C_2H_2$ gas mixture. At the end of the gradient layer we switched of the Cr targets and continued with the deposition of the a-C:H functional layer by a pure PACVD process in a mid-frequency glow-discharge process in a mixed $Ar/C_2H_2$ atmosphere at approximately $6.8 \cdot 10^{-3}$ mbar. The coating thickness of the functional a-C:H layer was approximately 1.5–2.0 μm.

### 2.2. Reciprocating ball-on-flat sliding wear test in dry conditions

A reciprocating ball-on-flat sliding wear test (SRV) was carried out using a SRV4® tribotest from Optimol Instruments. The friction and wear performances of the DLC coated samples were investigated over a broad range of temperatures (from room temperature to 480 °C) against two different uncoated counterpart materials (100Cr6 and $Al_2O_3$) without lubrication. The samples to be tested were heated from the bottom side; the actual temperature of the coating surface was measured with a thermocouple from the top side. Before starting the tribotests, the samples were kept in contact with the counterpart without any load at the testing temperature for 15 min in order to ensure a homogeneous and stable temperature distribution in the contact zone. Prior to the actual tribotest we performed a run-in phase of 2.5 min with an increasing normal load from 2 N to the actual nominal value of 5 N, and the following testing time was fixed to 10 min. The relative humidity was kept constant at 30–40% during all the tests. Further test parameters are given in Table 1. After testing, the wear volume, respectively the quantity of removed material, as well as the coefficient of friction were analyzed. To determine the quantity of removed material, the volume of each wear track was measured after the testing using confocal microscopy (μ-Surf from Nanofocus).

### 2.3. Coating hardness

The influence of the temperature on the integral indentation hardness $H_{IT}$ of the DLC coating was measured at room temperature on four samples that were previously tested on the reciprocating ball-on-flat sliding wear test at different temperatures (room temperature, 130 °C, 245 °C and 405 °C). All measurements were carried out on a Universal Nanomechanical Tester (UNAT) from ASMEC (Zwick/Roell) equipped with a Berkovich indenter. Two different series of measurements were carried out in order to measure the coating hardness as a function of the indentation depth:

a) A first series of measurements was performed using different indentation loads (10 mN, 20 mN, 50 mN, 100 mN and 200 mN), according to the ISO14577 guidelines [6].
b) A second series of Quasi Continuous Stiffness Measurements (QCSM) was done with continuously increasing indentation loads from 0.5 mN to 200 mN, as described by Praessler et al. [7]. However, using this method data obtained for indentation depths below 0.1 μm is not reliable since the influence of the tip rounding of the Berkovitch indenter becomes important and cannot be compensated.

### 2.4. Raman spectroscopy

In this study, Raman spectroscopy was used to analyze DLC coatings which were previously submitted to SRV-tribotests at room temperature and elevated temperatures as described above. Raman spectra have been collected at the coating surface outside the wear track and inside the wear track. The Raman spectra have been recorded with an InVia Raman reflex Renishaw spectrophotometer using visible excitation at 532 nm wavelength (3 mW at the sample). Scattered light was collected in backscattering (×50 objective, NA: 0.75) in the single linefocus mode (holographic grating 2400 gr/mm) using a fixed acquisition time of 0.1 s. All spectra have been baseline subtracted before being decomposed in two Gaussian contributions.

**Table 1**
SRV test parameters used for a reciprocated sliding wear test of a DLC coating tested against two different counterpart materials over a broad temperature range.

| Counterpart | Ø [mm] | Normal force [N] | Oscillating frequency [$s^{-1}$] | Stroke length [mm] | Temperature [°C] |
|---|---|---|---|---|---|
| Steel ball (100Cr6, 1.3505) | 10 | 5 | 5 | 3 | 45<br>90<br>105<br>135<br>175<br>210 |
| Ceramic ball ($Al_2O_3$) | 10 | 5 | 5 | 3 | 290<br>330<br>360<br>405<br>445<br>480 |