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Dependence between friction of laser interference patterned carbon and the thin film morphology

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ABSTRACT

Tetrahedral amorphous carbon coatings exhibit excellent tribological properties in terms of friction (~0.1) and wear (~10^{-9} mm^3/N/m). In this work, the dependence between micro structural changes due to laser structuring and the tribological properties of ta-C are discussed. The laser structuring is made by using a holographic technique called direct laser interference patterning (DLIP). Within this technique an 8 ns pulsed UV-laser (wavelength 355 nm) is used, to produce cross-like patterns with structural periods ranging from 2 μm to 10 μm. The influence of the patterns on the frictional behavior is investigated under linear reciprocating sliding conditions with ball on disk method and non-lubricated conditions. It is found that depending on the pattern period the friction is either increased or reduced compared to an unpatterned reference sample. The decrease of the friction coefficient is explained by a reduction of surface contact area and a high hardness of the non-ablated ta-C films. However, the increased friction results from thermally induced changes in the morphology of the ta-C film. This assumption is substantiated by thermal simulation of the DLIP process. Additionally the frictional properties of DLIP processed ta-C- and steel surfaces vs. steel probes with and without a ta-C coating are compared.

1. Introduction

Today's industry spends considerable efforts in optimization of processes to reduce energy losses in mechanical parts. An improved performance of mechanical parts is typically accompanied by an increased life cycle (reduced wear) and a reduced energy consumption (reduced friction). One route to achieve these requirements is to separate the basic material properties from the surface properties. Thus, the main function of a part remains intact but new advantageous surface properties can be generated. One major field of functionalized surfaces is tribological applications in order to reduce friction, wear and abrasion. By comparing different tribological coatings, diamond like carbon (DLC) films combine some of the most advantageous properties such as chemical inertness, low wear and low friction. Basically DLC-coatings can be divided in coatings with minor or major hydrogen contents [1]. Additionally, these coatings can be classified according to their sp^3-content. Within these definitions, coatings with a low hydrogen content (around 0,1–5%) and high sp^3-content (>70%) are called tetrahedral amorphous carbon (ta-C). These coatings offer an extreme high hardness and low friction even under non-lubricated conditions [2]. Ta-C coatings prepared with pulsed arc technology, exhibit empirical relations between the density (ρ), sp^3-content (F), elastic modulus (E) and hardness (h). The relation between sp^3-content and thin film density is given by [3]:

$$F = \frac{\rho - 1.92}{1.37}. \tag{1}$$

Furthermore, the density can be correlated with the elastic modulus [4] as follows:

$$\rho = 1.79 \left[g \cdot cm^{-3}\right] \cdot \left(1 + \frac{E}{780\,[GPa]} - \left(\frac{E}{1620\,[GPa]}\right)^2\right). \tag{2}$$

Thus, a higher elastic modulus corresponds to a higher density and concomitantly higher sp^3-content. Additionally, it has been observed that the thin film hardness is directly proportional to the elastic modulus [4]:

$$h = 0.1 \cdot E. \tag{3}$$

It has to be noted, that these relations are based on the variation of the sp^3-content in the ta-C thin films. A limiting factor of these empirical relations is the crystallinity of the sp^2-bonded carbon network. This property might influence the elastic modulus or the optical properties independent from the sp^3/sp^2-ratio [5,6].

The tribological properties of ta-C, especially the coefficient of friction (COF), correlate linearly to the sp^3-content of the thin film [7].

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This was demonstrated at least with thin films produced by cathodic arc processes and sp^3-contents between 75 and 87%, presenting COF between 0.117 and 0.084 (non lubricated), respectively [8]. However, if the carbon thin film morphology is crystalline graphitic or ultrananocrystalline graphitic, the thin DLC films might exhibit an ultra-low COF (<0.010) [8]. In addition, a major influence on the tribological performance of ta-C can be attributed to the relative ambient humidity. In general, it has been observed that the COF and the wear of the film are anticorrelates with the relative humidity [9].

Besides influencing the chemical and physical properties, the tribological interaction of the frictional partners can be tuned by geometrical features. Surface topographies can be stochastic or deterministic and might influence adhesive as well as abrasive interactions. If abrasive interactions dominate the tribological performance, polishing of the material surface typically can be used to reduce the COF. For instance, it was shown that the COF of 6 μm thick ta-C could be reduced from 0.15 (Ra = 100 nm) down to 0.1 by surface polishing (Ra = 10 nm) [10]. The reason is given by the removal of surface asperities (particles) and consequently minimizing abrasive interactions. Furthermore, the tribological performance of these films could be further improved by replacing the polishing process by a brushing process [10,11]. The brushing not only removes the particles but additionally results in a smooth and wavy surface. This waviness gives a reduced contact area and adhesive interactions between the frictional partners, respectively.

In contrast to stochastical surface topographies, specific deterministical (periodic) patterns can be used to reduce adhesive forces, to trap abrasion particles, or to build up hydrodynamic pressure by the introduction of lubricant reservoirs [12–14]. A technology that offers a high degree of flexibility in the surface pattern geometries is direct laser patterning. The fabrication of deterministic patterns on ta-C films using a focused laser beam and related frictional experiments were already demonstrated by Dumitru et al. [15]. But the surface patterns on the ta-C resulted in an increased friction coefficient as well as the destruction of the ta-C thin film. In contrast, direct laser interference patterning (DLIP) of ta-C films could demonstrate that a reduction of the friction coefficient using dot-like and line-like patterns with spatial periods of 5 μm is possible [12]. Otherwise, at the moment any studies describing the effect of laser induced graphitization as well as the spatial period size on the COF of DLIP-patterned ta-C and steel (100Cr6), respectively. This gap is discussed in the present publication.

2. Experimental

2.1. Ta-C thin film preparation

In this study, ta-C-films were produced by an industrial arc-coating process, based on laser-arc technology. In this method, the arc-process is induced by a pulsed infra-red laser (Nd-YAG-laser with 1064 nm wavelength and 500 Hz pulse frequency). All thin films were produced on stainless steel substrates, which were cleaned and polished prior to the experiments. During the thin film coating there was a pressure of ~10^{-4} Pa is maintained in the evaporation chamber. During the coating process, also micro particles are produced and remain embedded in the thin ta-C film. These particles lead to an increased surface roughness and thus also an increased wear and friction. Therefore, after the thin film deposition the ta-C coatings were brushed. The resulting film thickness was 2.5 μm with a roughness (R_a) of approximately 30 nm and an elastic modulus of ~450 GPa, corresponding to a film density of 2.85 g/cm^3.

2.2. Direct laser interference patterning

A line-like interference pattern can be generated by at least two coherent, polarized laser beams. The periodicity Λ is determined by the angle α between the laser beams, the wavelength λ and the refractive index n at the substrate surface according to:

$$\Lambda = \frac{\lambda}{2 \cdot n \cdot \sin(\alpha/2)}. \quad (4)$$

The spatial intensity I distribution is given by the squared absolute value of the total wave function. The total wave function E is the superposition of the overlapping electromagnetic waves E_j, which can be described as plane waves:

$$E = \sum_{j=1}^{n} E_j = \sum_{j=1}^{n} E_{j0} \cdot \exp \cdot i\left(\vec{k} \cdot \vec{r} - \omega \cdot t\right). \quad (5)$$

For two interfering laser beams, the intensity distribution is given by:

$$I = \frac{c\varepsilon_0}{2}|E|^2 = 2I_0 \cdot \left\{ \cos\left(\frac{4\pi x}{\lambda} \sin(\alpha/2)\right) + 1 \right\}, \quad (6)$$

where I_0 is the intensity of the laser beams, ε_0 the dielectric constant in vacuum and c the speed of light. Eq. (6) shows that the intensity distribution basically follows a cosine function. The laser experiments were made with a pulsed (pulse duration 8 ns, frequency 10 Hz) high power Nd:YAG Laser (from Spectra Physics) operated at 355 nm wavelength. The pattern period is controlled by the intersecting angle of the two laser beams. A mechanical shutter is used to control the number of laser pulses. For superimposed cross-like patternings the line-like patterned substrate was rotated by 90° and again structured by a line-like pattern.

2.3. Tribology

All frictional tests on ta-C thin films were made with a tribometer from CSM (NTR). The measurements are performed by loading a sphere, with a defined force on the ta-C test samples. The sphere is attached to a cantilever spring and the coefficient of friction is measured from the deflection of the cantilever. During the measurement the sample was moved in a linear reciprocating mode with a speed of 3 cm/s under the test sphere. The number of test cycles in Table 1 corresponds to a measurement length of 200 m and 5000 m. In this study the cantilever is equipped with 100Cr6 test spheres (diameter 6 mm) and operated normal loads of 100 mN (resolution 5 nN). Ta-C test spheres are made of 100Cr6 coated with 1 μm ta-C. All measurements were made under ambient conditions (relative humidity 45%, temperature 23 °C). Table 1 summarizes the test conditions.

3. Results and discussion

3.1. Interference patterning of ta-C

From previous experiments it is known that smaller contact areas between frictional partners are beneficial for lower friction [12]. Consequently ultra-low friction in a ball on disk setup was demonstrated

Table 1
Tribological test parameters.

Tribological parameters	
Linear velocity v	3 cm/s
Normal Load F_n	100 mN
Cycles	175,000
	4,375,000
Hertzian contact pressure	450 MPa
Ball material	100Cr6
Ball diameter	6 mm
Ball coating	ta-C 1 μm