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Tribological properties of textured diamond-like carbon coatings

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Abstract

This paper presents selected mechanical and tribological properties of DLC coatings (diamond-like carbon coatings) and the results of an applied texture to improve these properties under specific circumstances. It presents the results of the selection of parameters for the laser-texturing process of DLC coatings using a picosecond laser with a wavelength of 343 nm.

Keywords: DLC coatings; laser treatment; tribological properties

1. Introduction

Extending the life cycle of equipment and machinery and thus reducing wear and tear is one of the most important technological and economic challenges in twenty-first century industry. To overcome this problem, various technological approaches can be used, such as the selection of suitable materials, as well as the application of protective coatings. One of the coating materials that is gaining increasingly widely used coating material is DLC.

DLC stands for diamond-like carbon and it consists of amorphic carbon forms, mostly the sp^3 and sp^2 hybridisations. The sp^2 hybridisation (found in graphite) is responsible for good electrical conductivity and has a low coefficient of friction, while the sp^3 hybridisation (found in diamonds) is characterised by high hardness, chemical inertness and high wear resistance.

These coatings are used in various applications in which there is a need to reduce friction and improve wear resistance. They can be used as a solid lubricant for bearings of machines operating in harsh conditions – such as in a vacuum – and as coatings in the automotive industry. They are also used to increase the durability of cutting tools in the textile industry to coat nozzles used to stream abrasive materials such as glitter and for micro- and nano-electromechanical systems to improve their durability. An interesting application of DLC coatings is in medicine – due to their biocompatibility, they can be used as coatings for endoprostheses (Radek et al., 2020; Kaneko et al. 2021; Vanhulsel et al. 2007).

To further improve the tribological properties of the coated components used in specific applications, the production of a texture on the outer layer can be an efficient method. This is mainly due to the microreservoir effect. This occurs when an additional amount of lubrication is stored to improve friction properties evenly on the whole surface. Debris and worn particles can be stored in microdimples. This greatly improves friction properties by reducing wear. To apply the texture, laser micromachining can be used. Laser machining allows repeated, rapid and accurate production of various forms of texture (Molpeceres et al. 2007; Radek et al. 2014; Madej et al. 2015; Vicen et al. 2021, Radek et al. 2018; Radek, Bartkowiak 2011).

In order to maintain operational function using DLC coatings, the right application method and substrate material should be selected. For example, tungsten and chromium interlayers can be used to increase adhesion to the surface.

In this study, selected mechanical and tribological properties of DLC coatings were investigated. To test the quality of the material, a microstructure investigation and scratch tests were performed. The purpose of this study was to characterise the tribological properties of laser-textured DLC coatings.

2. Materials and methods

The study consists of two parts. In the first section, microstructure and mechanical properties analyses are performed. The second section contains a selection of optimal parameters to obtain required texture on the surface of the DLC-coated specimen.

To view the microstructure of the specimen, an analysis with a scanning electron microscope was performed. The hardness and modulus of elasticity were tested with a nanohardness tester. During the test, the indenter displacement and the required force were measured. DLC coatings were obtained using the following processes and temperatures:

- a-C: H by physical vapour phase PVD deposition by sputtering at <300°C,
- 350°C temperature of substrate material.

The test specimens were ring-shaped, made of 4H13 steel and coated with a-C:H:W layer.

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2.1. Microstructure and mechanical property analysis

The first part of the study was to examine the microstructure of the specimen. Figure 1 shows the thickness of the specimen interlayers. The thickness of the DLC coating was approximately 4.28 µm. A clear boundary line can be seen between the coating and the substrate. The coating was not porous and has no micro-damage.

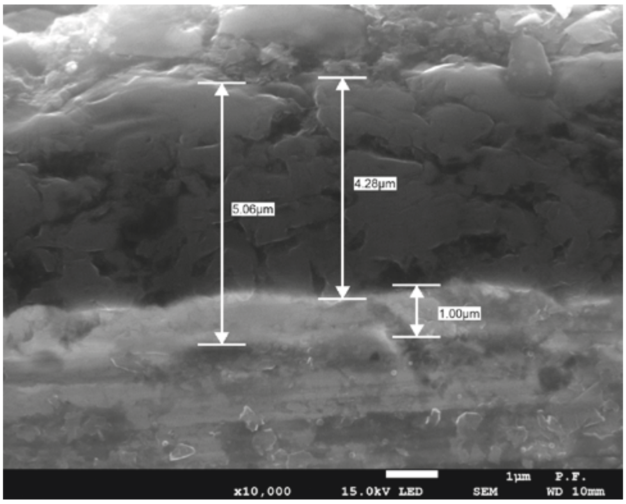

Fig. 1. DLC-coated specimen microstructure (own elaboration)

Figure 2 presents a linear distribution of the specimen chemical elements. The graph presents the composition of elements as a function of coating thickness. There is a cumulative amount of chromium in the range of 2 to 5 µm of the scanning area. This thin layer of chromium was designed to improve the adhesion of the coating. There is also a clear coating boundary of tungsten, which is a component that also enhances the adhesion of DLC to the substrate. Additionally, the diffusion of tungsten and chromium atoms into carbon atoms can be observed.

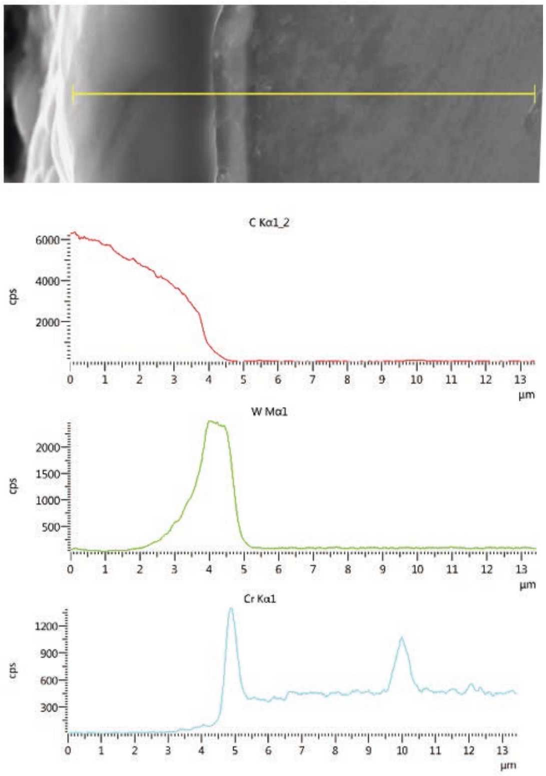

Fig. 2. Linear distribution of elements in the specimen (own elaboration)

The hardness and modulus of elasticity of coating and substrate were tested with a nanohardness tester (Table 1). During the test, the indenter displacement and the required force were measured. The average nanohardness and modulus of elasticity were calculated from ten measurements along with the standard deviation.

Table 1. Results of nanohardness test

Material	Nano hardness	Elastic modulus
DLC coating	7.55 ± 0.10	92.87 ± 2.05
4H13	5.60 ± 0.40	44.00 ± 4.30

Next, a scratch test of the prepared specimen was performed (Figure 3). A scratch test is a test of adhesion of the coating. It consists of making a crack with a penetrator with a gradual increase of the normal force and measurement of the force of resistance of the material. To obtain results, the critical force was measured – this is the smallest normal force that causes the coating to lose adhesion to the substrate. It can be seen that when the force is greater than 50 N (purple line), the coating starts to lose its adhesion.

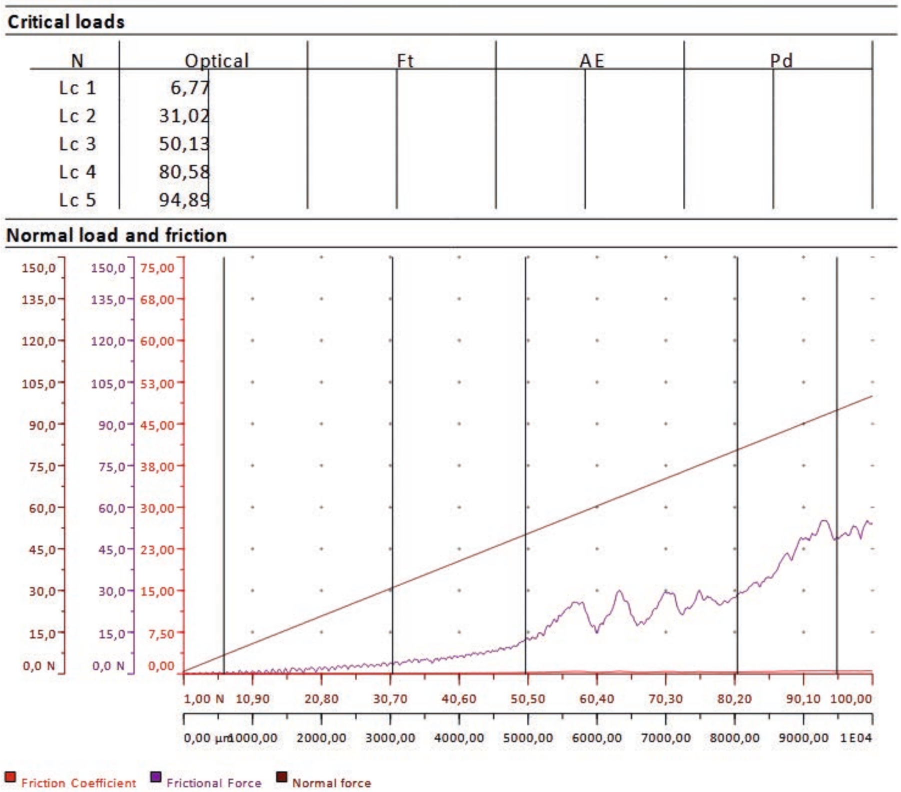

Fig. 3. Scratch test of DLC coated specimen (own elaboration)

2.2. Laser texturing of DLC coatings

Texturing of the DLC coating was accomplished using a Trumpf TruMICRO 5325c picosecond laser with an average max power of 5W, a pulse energy of up to 12.6 µJ, a beam quality of M^2<1.3, a maximum pulse frequency of 400 kHz and a 343 nm wavelength.

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First, the effect of laser radiation on the coating was investigated over a wide range of processing parameters. Next, a change of the laser power and pulse frequency at a constant scanning speed was performed. After selecting the proper parameters, the selection of laser- beam scanning speed was then conducted. It consisted of an evaluation of the impact of laser impulses on the surface of the coating with a change in scanning speed at a constant pulse frequency and laser power. The test was conducted for fourteen laser-head scanning speeds which varied by 5 mm/s. The selection of laser beam parameters was evaluated by observing the impact of the laser beam on the surface of the specimen. The highest fluence value and the visual quality (shape) and depth of the groove produced on the surface of the specimen were determining variables. Table 2 presents example values that were taken into consideration:

Table 2. Selected laser parameters and the result

No.	V [mm/s]	P [W]	f [kHz]	Pa [W]	Ie	I%	Io [µm]	In	F [J/cm²]	Maximal depth [µm]	Surface area [µm²]	Vertical distance [µm]
1	85	3.5	66.66	0.58	8.75	0.85	1.28	14	3.14	2.54	83.051	55.941
5	105	3.5	66.66	0.58	8.75	0.82	1.58	12	3.08	2.721	66.113	48.19
6	**110**	**3.5**	**66.66**	**0.58**	**8.75**	**0.81**	**1.65**	**11**	**3.07**	**2.219**	**54.217**	**43.022**
8	120	3.5	66.66	0.58	8.75	0.79	1.80	10	3.04	2.838	46.727	55.885
10	130	3.5	66.66	0.58	8.75	0.78	1.95	9	3.01	2.595	50.224	35.116
14	150	3.5	66.66	0.58	8.75	0.74	2.25	8	2.96	3.39	68.69	37.383

Where:
v – laser-head scanning speed [mm/s];
P – laser power [W];
Pa – average laser radiation power [W];
f – laser-pulse frequency [kHz];
Ie – laser-pulse energy [µJ];
Io – distance from the centre of subsequent pulses [µm];
Ln – number of pulses;
F – laser radiation fluency [J/cm^2].

The following laser parameters were selected:

- 70% laser power – 3.5 W;
- frequency 66.6 kHz;
- pulse divider – 2;
- laser-head scanning speed – 110 mm/s.

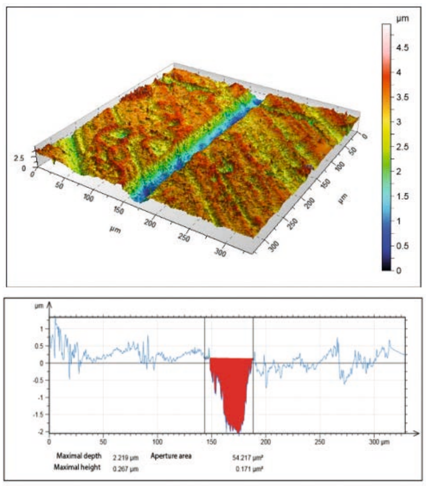

Fig. 4. Surface topography of coated specimen after treatment with optimal laser process parameters (own elaboration)

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Figure 4 presents the surface topography of the specimen with the created groove after laser treatment with optimal parameters. The depth was measured on a Talysurf CCI Lite non-contact surface profiler.

3. Conclusions

The following conclusions can be drawn on the basis of the research performed so far and the analysis of results:

- It is possible to obtain parameters of the laser process that can produce a texture with a picosecond UV laser with a depth smaller than the depth of the coating, thus the DLC coating remains on the whole surface of the specimen.
- Micro-textures with a depth of about 2.5 μm can act as micro-reservoirs and have an impact upon tribology properties.
- A concentrated laser beam can modify the state of the material layer and thus have an impact upon the performance of the surface.
- The examined DLC coating lost their adhesion at a force greater than 50 N.
- In the next stage, we plan to run the corrosion resistance test and the surface free energy test after the texturing process because DLCs have demonstrated resistance to acid and alkaline media.

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