Selection of Process Parameters for Laser Texturing of DLC Coatings

KALINOWSKI Artur[1,a *], RADEK Norbert[2,b], SĘK Piotr[2,c] , PIETRASZEK Jacek[3,d]
and ORMAN Łukasz[4,e]

[1]Kielce University of Technology, Faculty of Mechatronics and Mechanical Engineering,
Al. 1000-lecia P.P. 7, 25-314 Kielce, Poland

[2]Kielce University of Technology, Faculty of Mechatronics and Mechanical Engineering,
Al. 1000-lecia P.P. 7, 25-314 Kielce, Poland

[3]Cracov University of Technology, Faculty of Mechanical Engineering,
Al. Jana Pawła II 37, 31-864 Kraków, Poland

[4]Kielce University of Technology, Faculty of Geomatics and Energy Engineering,
Al. 1000-lecia P.P. 7, 25-314 Kielce, Poland

[a]akalinowski@tu.kielce.pl, [b]norrad@tu.kielce.pl, [c]psek@tu.kielce.pl,
[d]jacek.pietraszek@pk.edu.pl, [e]orman@tu.kielce.pl

Keywords: Diamond-Like Carbon, Coatings, Laser Texturing

Abstract. This paper presents the results of the selection of parameters for the DLC coatings laser texturing process using a picosecond laser with a wavelength of 343 nm. It also shows the level of precision with which it is possible to generate a texture with this technology and examples of possible shapes created using TruTOPS PFO software with their selection for the best texture quality.

Introduction

Forming the micro-geometry of friction surfaces is a very common issue in modern machine constructions. Technological progress, including in the field of laser techniques, enables very high precision surface modification. Laser texturing allows for making micro-cavities on the surface of a given material in a quick and repeatable way.

Laser texturing is a type of subtractive micromachining process. The size of the material to be removed is in the range of micro and millimeters. The energy of the laser beam is used to remove material. Laser micromachining is a method commonly used when high and repeatable dimensional accuracy is required and for materials that are difficult to process by other methods. Laser texturing involves forming a desired geometric structure and/or distribution of physicochemical and mechanical properties on the surface of a processed material [1, 2].

The area of the beam impact on the material is determined by the size of the laser spot in focus. The time of the beam pulse is particularly important since different mechanisms of interaction with the material can be used depending on the intensity of the radiation and the exposure time. Pulses longer than 1 nanosecond are called long pulses. Pulses with durations between 1 picosecond and 1 nanosecond are called short pulses, and those with durations less than 1 picosecond are referred to as ultrashort pulses [3].

The crucial aspect is the proper selection of process parameters to obtain texture elements with desired and reproducible geometries and physicochemical properties. The size of the heat-affected zone, or lack of it, depends on the duration of the laser pulses. Treatment with long pulses leaves distinct remelting marks and heat-affected material alterations. Laser ablation induced by picosecond and femtosecond laser pulses is called cold ablation because no heat-affected zone, in its traditional sense, is observed in the material [4].

In recent years there has been great progress in the development of research and application topics related to carbon materials. It includes obtaining diamond-like coatings, DLC (Diamond-Like Carbon), and applying them by PVD and CVD methods [5-7]. DLC coatings can be used in a variety of tribological pairs [8].

The choice of using UV wavelength laser is because DLC coatings are mainly transparent to the visible and IR spectrum of light but can absorb UV radiation.

Experimental

The test specimens were 4H13 steel samples with antiwear a-C:H DLC coating containing vanadium and chromium interlayers. The coating was applied using PVD technology. The thickness of the coating was approximately 1.5 µm. DLC coatings are characterized by very good mechanical properties (including low coefficient of friction and high hardness). These properties make DLC coatings widely used for machine parts that are subjected to high loads and increased wear and subjected to increased wear. The composition of the steel used was as follows (wt.%): C: 0.36-0.45, Mn: 0.50-0.80, Cr: 12.0-14.0, Si: 0.60-0.80, Mo: 0.5-0.7, V: 0.2-0.3, Ni: 0.1-0.60, P: max 0.04, S: max 0.03, and the remainder is iron.

The process of PVD deposition of antiwear thin coatings is carried out at increased temperature. The coating was obtained by the following processes and temperatures:

- a-C:H by physical vapor deposition PVD sputtering at < 300°C;
- substrate material temperature 350°C.

Laser texturing of coatings is used to create a reservoir effect on the surface of interacting coatings. This phenomenon occurs when wear particles or a lubricant are stored in the cavities created by the texturing. This results in better distribution of the lubricant and also has a significant effect on reducing wear. The implementation of the experimental plan was divided into two stages. In the first stage, the selection of appropriate laser operating parameters was made in order to obtain a texture of optimal quality. The cavity quality, its width, and depth were taken into consideration. The depth was measured on a Talysurf CCI Lite optical profilometer. Six texture shapes were then designed using TruTops PFO software. A ring-shaped specimen of 4H13 steel with a DLC coating was sketched in the software along with different textures, and then its surface was divided into 6 regions to create texture on the surface of one specimen. The texture shapes were then examined for surface quality on a Hirox KH-8700 digital microscope.

Results and Discussion

Parameter selection began by determining the optimal laser power in terms of the highest fluence value and the quality of the groove produced on the surface of the specimen by laser. In order to find the optimal laser texturing conditions, an experiment was conducted. It consisted of evaluating the effect of the laser pulses on the coating surface while changing the scanning speed, with constant pulse frequency and laser power. A test was performed for 14 scanning speeds varied by 5 mm/s. The selection of the laser beam parameters was evaluated by observing the laser beam impact trace. Geometry evaluation was done using Mountains®8 software for surface topography. The evaluation took into account:

- groove depth,
- the presence and shape of the flotation,
- the shape of the groove.

The diameter of the laser spot in focus was determined to be 18.2 μm, and the area of interaction of the focused laser beam according to the specifications of the TruMicro 5000 laser was 259.2μm^2. Calculations from [4] were used to determine the other resulting parameters.

In order to select the optimal parameters for the laser texturing process, a preliminary test was carried out on one of the samples. The following laser parameters were used to perform the test:

- 70% laser power - adjustable power of 3.5 W;
- frequency 66.6 kHz;
- pulse divider - 2.

The examination of microstructure was performed using the Talysurf CCI optical profilometer for surface geometry structure investigation. The system enables the analysis of the geometric structure of the surface with a vertical resolution of up to 0.01 nm. Data analysis was performed using TalyMap Platinum 6.2.7200 software.

Considering the results from the optical measuring machine, sample No. 6 was selected at a beam speed of 110 mm/s with a maximum groove depth of 2.219 μm and a horizontal distance of 43.022 μm. Table 1 shows the parameter selection along with the calculated parameters.

Table 1. *Selecting the scanning speed of the TruMicro 5000 picosecond laser head*

No.	**V [mm/s]**	**P [W]**	**f [kHz]**	**Pa [W]**	**Ie**	**I%**	**Io [μm]**	**In**	**F [J/cm^2]**	**Maximal depth**	**Surface area [μm^2]**	**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
2	90	3.5	66.66	0.58	8.75	0.85	1.35	13	3.13	3.331	93.975	48.19
3	95	3.5	66.66	0.58	8.75	0.84	1.43	13	3.11	3.068	91.693	48.19
4	100	3.5	66.66	0.58	8.75	0.83	1.50	12	3.10	3.493	132.308	48.19
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**
7	115	3.5	66.66	0.58	8.75	0.80	1.73	11	3.06	2.714	79.329	67.759
8	120	3.5	66.66	0.58	8.75	0.79	1.80	10	3.04	2.838	46.727	55.885
9	125	3.5	66.66	0.58	8.75	0.79	1.88	10	3.03	2.919	59.424	43.13
10	130	3.5	66.66	0.58	8.75	0.78	1.95	9	3.01	2.595	50.224	35.116
11	135	3.5	66.66	0.58	8.75	0.77	2.03	9	3.00	2.724	55.68	56.892
12	140	3.5	66.66	0.58	8.75	0.76	2.10	9	2.99	2.315	42.193	31.666
13	145	3.5	66.66	0.58	8.75	0.75	2.18	8	2.97	2.547	50.034	42.954
14	150	3.5	66.66	0.58	8.75	0.74	2.25	8	2.96	3.39	68.69	37.383

where:

- ν – laser head scanning speed [mm/s];
- P – laser power [W];
- Pa – average laser radiation power [W];
- f – laser pulse frequency [kHz];
- Ie – single pulse energy [μJ];
- Io – the distance between pulse centers [μm];
- Ln – Number of pulses per workpiece point;
- F – fluence of laser radiation [J/cm^2];

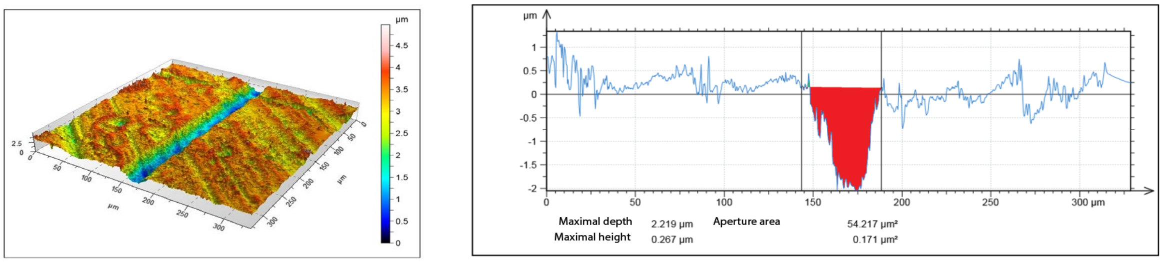

Fig. 1. *Surface structure after treatment with the selected laser parameters – 110 mm/s laser head scanning speed.*

Fig. 1 shows the surface structure analysis after a single laser beam passage with the selected parameters.

Once the laser processing parameters were selected, the second stage of the experiment was started – texture shape selection. The texture shapes generated using TruTops PFO software were as follows:

- grit with 150 µm distance between beam passes;
- spiral with 100 µm distance between beam passes;
- lines with a distance between beam passes of 400 µm;
- circles 60 µm in diameter with a distance between centers of 100 µm;
- crescents - an arc with a radius of 60 µm and an angle of 180°;
- points with a diameter of 30 µm and a distance of 100 µm.

Fig. 2 shows the shapes of textures taken into consideration.

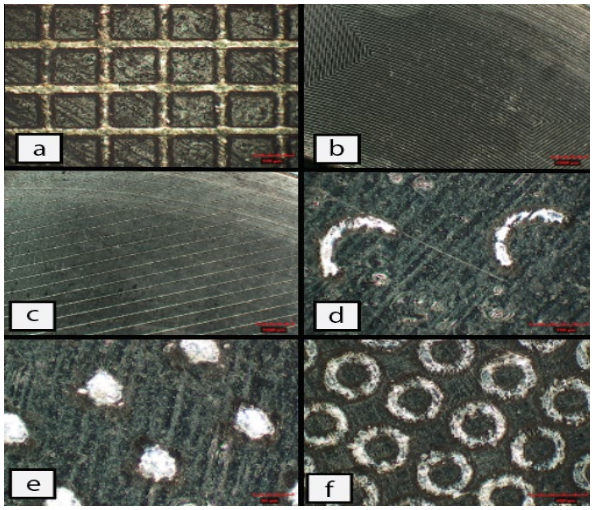

Fig. 2. *Different shapes of the texture with given magnification: a) Grid x2000 b) Spiral x35 c) Lines x35 d) Half circles x2000 e) Points x2000 f) Circles x2000.*

The quality of the coating after texture generation did not deteriorate. The best texture quality (in terms of groove quality) is shown by the grid and spiral texture. The lines are clearly outlined, and their shape is regular. The point-shaped texture with a diameter of 30 µm shows some shape irregularity. The points do not have a uniform character. The circle-shaped texture also does not show the required repeatability of the cavity depth. The semi-circle-shaped texture like other non-orthogonal textures does not achieve the required coating depth uniformity. The areas where the texture was not made to the required depth are visible. Fig. 3 shows an example of the surface geometric texture results using a Hirox optical microscope. It can be seen that the groove depth is approximately 2 µm. This value matches the values achieved in the first stage of the experiment on the selection of laser texturing parameters.

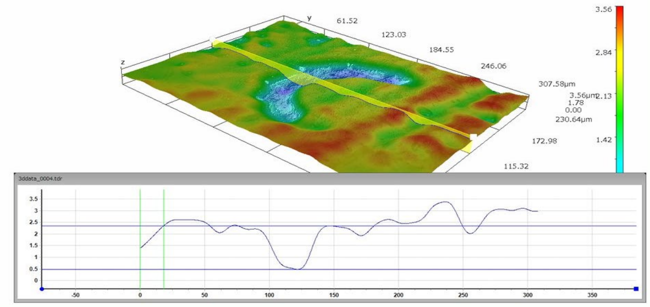

Fig. 3. *DLC coating surface microstructure after applying one type of texture.*

Summary

The aim of this work was to demonstrate the technological capabilities of texturing DLC coatings using a picosecond laser with a wavelength in the UV spectrum at which DLC coatings exhibit light absorption, making it possible to perform texturing on them. This laser is available at the Centre for Laser Technologies of Metals at the Kielce University of Technology. This paper presents the selection of parameters of the laser texturing process on the DLC coating applied on the substrate made of 4H13 steel. The parameters were chosen to produce grooves on the coating with a depth of about 2.13 µm. After selecting different texture shapes and examining them using microscopy, it was found that the best texture quality in terms of groove shape occurred for orthogonal shapes, i.e., shapes such as a grid or straight lines.

The presented results may be useful for people interested in significantly increasing the wear resistance of parts of machines and devices, e.g. biotechnological apparatus [9], chemical accessories [10-12], internal combustion engine accessories [13], or highly responsible elements of weapons [14, 15]. The analyzed process can also be an interesting experimental example for the analysis of adjustment calculus [16] and non-parametric methods [17-19].

References

[1] J. Pietraszek, N. Radek, A.V. Goroshko. Challenges for the DOE methodology related to the introduction of Industry 4.0, Production Engineering Archives 26 (2020) 190-194. https://doi.org/10.30657/pea.2020.26.33

[2] N. Radek, A. Szczotok, A. Gądek-Moszczak, R. Dwornicka, J. Bronček, J.. Pietraszek. The impact of laser processing parameters on the properties of electro-spark deposited coatings, Archives of Metallurgy and Materials 63 (2018) 809-816. https://doi.org/10.24425/122407

[3] W. Żórawski, R. Chatys, N. Radek, J. Borowiecka-Janrozek. Plasma sprayed composite coatings with reduced friction coefficient, Surface & Coatings Technology 202 (2008) 4578-4582. https://doi.org/10.1016/j.surfcoat.2008.04.026

[4] P. Sęk. Production and properties of textured surfaces, Ph.D. thesis, Kielce University of Technology, Kielce, 2014.

[5] M. Madej, D. Ozimina, K. Kurzydłowski, T. Płociński, P. Wieciński, M. Styp-Rekowski, M. Matuszewski. Properties of diamond-like carbon coatings deposited on CoCrMo alloys, Transactions of FAMENA 39/1 (2015) 79-88.

[6] M. Madej, K. Marczewska-Boczkowska, D. Ozimina. Effect of tungsten on the durability of diamond-like carbon coatings in the chemical industry, Przemysł Chemiczny 93 (2014) 500-505.

[7] K. Molewski, J. Kudliński, M. Madej, D. Ozimina. The interaction between diamond like carbon (DLC) coatings and ionic liquids under boundary lubrication conditions, Metalurgija 56 (2017) 55-58.

[8] M. Styp-Rekowski, E. Mańka, M. Matuszewski, M. Madej, D. Ozimina. Tribological problems in shaft hoist ropes wear process, Industrial Lubrication and Tribology 67 (2015) 157-164. https://doi.org/10.1108/ILT-01-2014-0004

[9] E. Skrzypczak-Pietraszek. Phytochemistry and biotechnology approaches of the genus Exacum. In: The Gentianaceae - Volume 2: Biotechnology and Applications, 2015, 383-401. https://doi.org/10.1007/978-3-642-54102-5_16

[10] M. Zenkiewicz, T. Zuk, J. Pietraszek, P. Rytlewski, K. Moraczewski, M. Stepczyńska. Electrostatic separation of binary mixtures of some biodegradable polymers and poly(vinyl chloride) or poly(ethylene terephthalate), Polimery/Polymers 61 (2016) 835-843. https://doi.org/10.14314/polimery.2016.835

[11] M. Dobrzański. The influence of water price and the number of residents on the economic efficiency of water recovery from grey water, Technical Transactions 118 (2021) art. e2021001. https://doi.org/10.37705/TechTrans/e2021001

[12] I. Nová, K. Fraňa, T. Lipiński. Monitoring of the Interaction of Aluminum Alloy and Sodium Chloride as the Basis for Ecological Production of Expanded Aluminum. Physics of Metals and Metallography 122 (2021) 1288-1300. https://doi.org/10.1134/S0031918X20140124

[13] M. Kekez, L. Radziszewski, A. Sapietova. Fuel type recognition by classifiers developed with computational intelligence methods using combustion pressure data and the crankshaft angle at which heat release reaches its maximum, Procedia Engineering 136 (2016) 353-358. https://doi.org/10.1016/j.proeng.2016.01.222

[14] B. Szczodrowska, R. Mazurczuk. A review of modern materials used in military camouflage within the radar frequency range, Technical Transactions 118 (2021) art.e2021003. https://doi.org/10.37705/TechTrans/e2021003

[15] A. Kubecki, C. Śliwiński, J. Śliwiński, I. Lubach, L. Bogdan, W. Maliszewski. Assessment of the technical condition of mines with mechanical fuses, Technical Transactions 118 (2021) art. e2021025. https://doi.org/10.37705/TechTrans/e2021025

[16] T. Styrylska, J. Pietraszek. Numerical modeling of non-steady-state temperature-fields with supplementary data. Zeitschrift fur Angewandte Mathematik und Mechanik 72 (1992) T537-T539.

[17] J. Pietraszek. Response surface methodology at irregular grids based on Voronoi scheme with neural network approximator. 6th Int. Conf. on Neural Networks and Soft Computing JUN 11-15, 2002, Springer, 250-255. https://doi.org/10.1007/978-3-7908-1902-1_35

[18] J. Pietraszek, E. Skrzypczak-Pietraszek. The uncertainty and robustness of the principal component analysis as a tool for the dimensionality reduction. Solid State Phenom. 235 (2015) 1-8. https://doi.org/10.4028/www.scientific.net/SSP.235.1

[19] J. Pietraszek, R. Dwornicka, A. Szczotok. The bootstrap approach to the statistical significance of parameters in the fixed effects model. ECCOMAS 2016 – Proc. 7th European Congress on Computational Methods in Applied Sciences and Engineering 3, 6061-6068. https://doi.org/10.7712/100016.2240.9206