TRIBOLOGICAL PROPERTIES OF ELECTRO-SPARK DEPOSITED COATINGS AFTER LASER TREATMENT

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Abstract
The main objective of the present work was to determine the influence of laser treatment on microstructure, microhardness, surface geometric structure, porosity and tribological properties of coatings deposited on C45 carbon steel by the electro-spark deposition (ESD) process. The studies were conducted using WC-Cu electrodes produced by the powder metallurgy route.

Key words: *electro-spark deposition; laser treatment; coating; properties*

INTRODUCTION
The process of material growth resulting from electro-erosion is known as electro-spark alloying (ESA) or electro-spark deposition (ESD). The erosion of the anode and the spark discharges between the electrodes result in the formation of a surface layer with properties different from those of the base material (*Chang-bin, Dao-xin, Zhan, & Yang, 2011*; *Antoszewski, Evin, & Audy, 2008*; *Radek, Sladek, Broncek, Bilska, & Szczotok, 2014; Padgurskas, Kreivaitis, Rukuiza, Mihailov, Agafii, Kriukiene, & Baltusnikas, 2017*).
Electro-spark deposition is a cheap high-energy process. Developed in the post-war period, the technology has been frequently modified. Its main advantages are the ability to select precisely the area to be modified, the ability to select the coating thickness, which may range from several to several dozen micrometers, good adhesion of a coating to the substrate, and finally, inexpensive and simple equipment for coating deposition.
Electro-spark deposited coatings have some disadvantages but these can be easily eliminated. One of the methods is laser beam machining (LBM); a laser beam is used for surface polishing, surface geometry formation, surface sealing or for homogenizing the chemical composition of the deposited coatings (*Radek, Wajs & Luchka, 2008; Radek, Pietraszek, & Antoszewski, 2014*; *Pietraszek, Radek, & Bartkowiak, 2013; Radek & Konstanty, 2012; Scendo, Radek & Trela, 2013*).
Analysis of properties of coatings requires many methods (*Radziszewski, 2004; Szczotok, 2015; Korzekwa, Gadek-Moszczak, & Bara, 2016; Pietraszek, Gadek-Moszczak & Torunski, 2014*). There are many alternative technologies for producing coatings and material properties improvements in relation to ESD technology (*Dudek & Włodarczyk, 2010; Ulewicz, 2015*).
The work discusses the properties of electro-spark deposited WC-Cu coatings under applied laser treatment. The properties were established based on the results of a microstructure analysis, surface geometric structure, microhardness, porosity and tribological studies.

MATERIALS AND METHODS
The working electrode (a stationary) was made from C45 carbon steel. The elemental composition of the steel was as follows (wt.%): C: 0.42 – 0.50, Mn: 0.50 – 0.80, Si: 0.10 – 0.40, P: 0.04, S: 0.04.
In the experiment, the coatings were electro-spark deposited with using a WC-Cu (50% WC and 50% Cu) electrode with a cross-section of 4 x 6 mm (the anode) - onto samples made of carbon steel C45 (the cathode). The main characteristics of the powders used in this work are included in Table 1.
The powders were mixed for 30 minutes in the chaotic motion Turbula T2C mixer. The mixture was then poured into rectangular cavities of a graphite mould, each 6×40 mm in cross section, and consolidated by passing an electric current through the mould under uniaxial compressive load. A 3 minute

hold at 950°C and under a pressure of 40 MPa permitted obtaining electrodes of porosity <10% and strength sufficient to maintain integrity when installed in the electrode holder.

Tab. 1 Powders used to manufacture WC-Cu electrodes

Powder	Particle size μm	Producer
WC	~0.2*	OMG
Cu	~0.04*	NEOMAT

** measured using Fisher Sub-Sieve Sizer*

This method offers high efficiency in production of sintered parts, at elevated temperatures, assists in protecting metallic powders against oxidation. The protection is attributed to the formation of a CO/CO_2 reducing atmosphere inside the graphite mould which, in the old-type equipment shown in Figure 1, is exposed to air. The following parameters were assumed to be optimal for ESA (*Radek & Konstanty, 2012*). The samples with electro-spark deposited coatings were laser-modified using the following parameters (*Scendo, Radek & Trela, 2013*).

Fig. 1 Hot pressing operation carried out in air

RESULTS AND DISCUSSION

A microstructure analysis was conducted for WC-Cu coatings before and after laser treatment using a scanning electron microscope Joel JSM-5400.

Figure 2 shows the microstructure of an ESD WC-Cu coating. It is clear that the thickness of the obtained layer varied from 36 to 60 μm, whereas the heat affected zone (HAZ) ranged from 20 to 30 μm into the substrate. Figure 2 also reveals a clear boundary between the coating and the substrate and pores within the coating. The ESD WC-Cu coatings were modified by the laser treatment, which caused changes in their composition. The laser treatment homogenizes the coating chemical composition, causes structure refinement, and crystallization of non-equilibrium phases due to the occurrence of temperature gradients and high cooling rates.

The laser-modified outer layer does not possess microcracks or pores (Fig. 3). There is no discontinuity of the coating-substrate boundary. The thickness of the laser-treated WC-Cu coatings ranges from 40 to 62 μm. Moreover, the heat affected zone (HAZ) is in the range of 25 to 35 μm, and the content of carbon in the zone is higher.

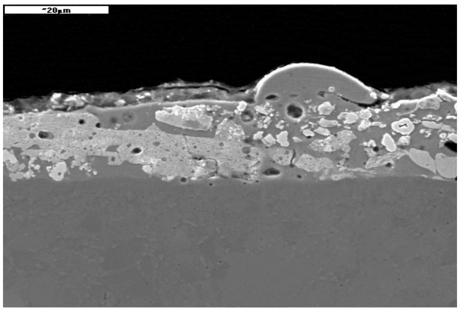

Fig. 2 WC-Cu coating microstructure after electro-spark alloying

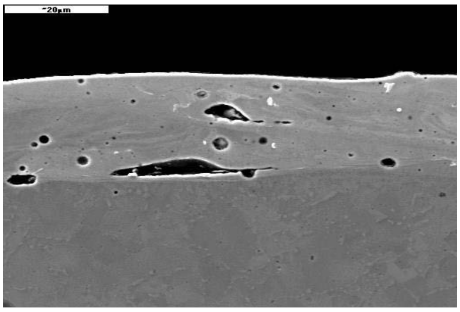

Fig. 3 Microstructure of the electro-spark alloying WC-Cu coating after treatment with an Nd:YAG laser

Microhardness testing was performed according to the Vickers method with a Microtech MX3 tester under the load of 40 G (0.4 N). Penetrator indentations were made on metallographic sections in three zones: in the coating (white layer), in the melted zone of coating (MZC), in the heat affected zone (HAZ), and in the base material (C45). Figure 4 summarizes the microhardness test results.

Laser treatment slightly decreased the microhardness of the ESD coatings. Laser irradiation reduced the microhardness of the WC-Cu coatings by 9% relative to the untreated coatings. The minor micro-hardness reduction after the laser treatment may improve the plastic properties of the coatings, which is important for the tools or machine elements operating under large loads, for example, drilling equipment in the mining industry or press elements used for ceramic building materialproduction. This effect may result from the dissolution of carbides.

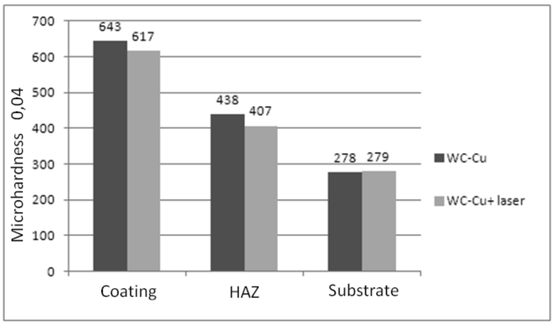

Fig. 4 Microhardness measurements for the WC-Cu coating before and after laser treatment

Surface geometric structure (SGS) substantially influences many processes that occur in the outer layer (*Miller, Adamczak, Świderski, Wieczorowski, Łętocha & Gapiński, 2017*).

Measurements of surface geometric structure (SGS) were carried out at the Laboratory of Computer Measurements of Geometric Quantities of the Kielce University of Technology. Those were performed using Talysurf CCI optical profiler that employs a coherence correlation algorithm patented by Taylor Hobson company. The algorithm makes it possible to take measurements with the resolution in the axis *z* below 0.8 nm. The result of measurements is recorded in 1024 x 1024 measurement point matrix, which for the x10 lens yields the 1.65 mm x 1.65 mm measured area and the horizontal resolution 1.65 μm x 1.65 μm.

Three-dimensional surfaces and their analysis with TalyMap Platinum software made it possible to precisely identify the geometric structure of the surfaces under consideration. Table 2 provides major parameters of the surface geometric structure of the examined specimens. Figure 5 present images of surface topography before and after laser treatment.

A greater value of the mean arithmetic deviation of surface roughness *Sa*, a basic amplitude parameter in the quantitative assessment of the state of the surface under analysis, was recorded for the specimen after the laser treatment, for the specimen before the laser treatment the value of this parameter was be almost 50% smaller.

A similar tendency is observed for the root mean square deviation of surface roughness *Sq*. Complementary information on how the surface of examined elements is shaped is provided by amplitude parameters, namely the coefficient of skewness (asymmetry) *Sku* and the coefficient of concentration (kurtosis) *Ssk*. Those parameters are sensitive to occurrence of local hills or valleys, and also defects on the surface. The parameter *Ssk* has a positive value for both specimens, the value is close to zero for the specimen before treatment, which indicates the symmetrical location of the distribution of ordinates with respect to the mean plane. The values of kurtosis that were obtained are close to *Sku* = 3, which indicates that the distribution of ordinates for both specimens is close to normal distribution.

Tab. 2 Parameters of the surface geometric structure

SGS parameters	Coating	
	WC-Cu	WC-Cu + laser
Sa [μm]	4.02	6.95
Sq [μm]	5.24	8.48
Ssk	0.15	0.02
Sku	3.89	2.77
Sp [μm]	26.44	34.03
Sv [μm]	21.21	66.76
Sz [μm]	47.65	100.80

Before laser treatment, the specimen had random isotropic structure (Iz = 88.52%), whereas after the treatment, that became a periodic structure, located in the transient area between isotropic and anisotropic structures (Iz = 55.32%). That is confirmed by the shape of the autocorrelation function of both surfaces, for the surface before treatment, the shape is circular and symmetrical, whereas for the surface after treatment, it is asymmetrical and elongated.

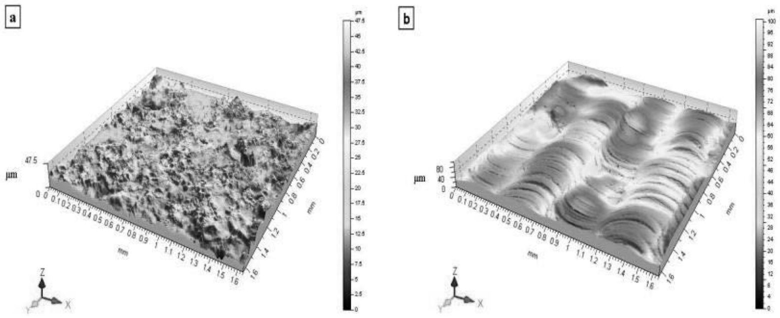

Fig. 5 Specimen surface topography: a) before laser treatment, b) after laser treatment

For assess the degree of porosity of the coatings tested WC-Cu before and after laser treatment, quantitative image analysis was performed using software supplied with the SIS which (SEM) Philips XL30 / LaB6. In the analysis guided by the principle of Cavalieri-Hacquerta according to which, a measure of the porosity can be shares of the pores:

- volume (the ratio of the total volume of voids to the total volume of the fragment of the coating),
- surface (the ratio of the total pore area to the total area analyzed grinding),
- the length of the control section (the ratio of the total length of the strings passing through the pores of the length of the analyzed section of the measurement plane grinding).

Tab. 3 Results of the surface porosity for the WC-Cu coating before and after laser treatment

Coating	Porosity % Number of measurement			Average value %
	1	2	3	
WC-Cu	5.7	6.3	3.5	5.2
WC-Cu +laser	0.4	0.2	0.1	0.2

Results of the surface porosity for the WC-Cu coating before and after laser treatment are shown in Table 3. Analyzing the table it can be seen that the applied coatings have a higher porosity with respect to the coating after laser treatment. Laser treatment reduced the porosity of the coatings more than 20 times. The porosity of the coatings WC-Cu was located in the range of 3.7 - 6.3%, and after laser treatment was 0.1 - 0.4%. Lower porosity of the WC-Cu coatings by positive influence on their performance characteristics, improving their corrosion resistance, adhesion and microhardness.

Seizure resistance tests were carried out using T-09 tribotester, in which the friction pair consisted of a cylinder and two prisms. Prisms with deposited WC-Cu coatings and C45 steel (laser treated and untreated) acted as specimens, whereas a roller of hardened carbon steel, ϕ6.3 mm in diameter, was used as a counter-specimen. In tests, three kinematic pairs were employed to investigate different material options, which made it possible to average experimental results. During the test, paraffin oil bath lubrication was used.

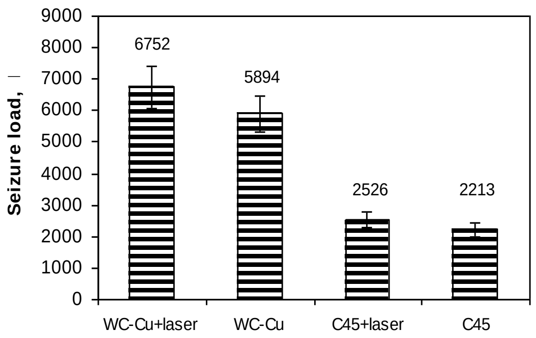

Fig. 6 Average values of seizure load

Figure 6 presents cumulative information on average values of seizure load for specimens before and after laser treatment. Those indicate that laser treatment resulted in an increase in the load that produced seizure both for electro-spark deposited coatings and for C45 steel.

CONCLUSIONS

1. A concentrated laser beam can be effective in modifying the state of the outer layer of electro-spark coatings and thus can modify their functional properties.
2. Laser irradiation of coatings resulted in the healing of micro-cracks and pores.
3. Parameters of surface geometric structure of electro-spark coatings have lower values when compared with SGS parameters of coatings after laser treatment.
4. Laser treatment caused an increase in the load at which seizure occurred for the tested materials. For laser-treated WC-Cu coatings, the value of the load is approx. 13% higher when compared to coated specimens without laser treatment.
5. Laser treatment caused a 9% decrease in the microhardness of the electro-spark alloying WC-Cu coatings.
6. Coatings after laser treatment are less porosity (more than 20 times).

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