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THE IMPACT OF LASER PROCESSING ON THE PERFORMANCE PROPERTIES OF ELECTRO-SPARK COATINGS

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Abstract. The main objective of the present work was to determine the influence of laser beam processing (LBP) on microstructure, microhardness, surface geometric structure, adhesion tests and tribological properties of coatings deposited on C45 carbon steel by the electro-spark deposition (ESD) process. The coatings were deposited by means of an EIL-8A. The laser processing was performed with an Nd:YAG, BLS 720 system. The studies were conducted using WC-Cu electrodes produced by the powder metallurgy route. The tests show the laser-treated electro-spark deposited WC-Cu coatings are characterized by higher adhesion and seizure resistance which come at the expense of lower microhardness. In addition, WC-Cu coatings after laser treatment had lower values of parameters of the surface geometric structure. The laser treatment process causes the homogenization of the chemical composition, structure refinement and healing of microcracks and pores of the electro-spark deposited coatings. Laser treated ESD coatings can be applied in sliding friction pairs and as protective coatings.

1 INTRODUCTION

A number of modern surface processing methods use an energy flux. The examples include electro-spark deposition (ESD) and laser beam processing (LBP). Electro-spark deposition is a cheap high-energy process. The method was first used in the USSR in the 1940s almost simultaneously with the destructive electrical discharge machining. The ESD technique was studied intensively in the 1960s. In the next decade, it was commonly applied to deposit hard-melting materials on selected metals and alloys, mainly steel. Polish scientists became interested in electro-spark alloying of coatings as early as in the 1980s.

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, cheap and simple equipment for coating deposition.

The processes of coating formation on metal parts including electro-spark deposition involve mass and energy transport accompanied by chemical, electrochemical and electro-thermal reactions [1]. Today, different electro-spark deposition techniques [2-3] are used; they are suitable for coating formation and surface microgeometry formation [4, 5]. Coatings produced by electro-spark deposition are applied:

1. to protect new elements,
2. to recover the properties of worn elements.

The electro-spark deposition coating is characterized by a non-etching structure. The surface layer is constituted in environment of local high temperature and high pressure. Electro-machining is characterized by [6]:

- shock wave pressure coming from electric spark is $(2\text{-}7)\cdot 10^3$ GPa,
- temperature reaching $(5\text{-}40)\cdot 10^3$ ºC.

Electro-spark deposited coatings have some disadvantages but these can be easily eliminated. One of the methods is laser beam machining; a laser beam is used for surface polishing, surface geometry formation, surface sealing or for homogenizing the chemical composition of the deposited coatings [7, 8]. One of the advantages of laser-treated electro-spark coatings will include: lower roughness, lower porosity, better adhesion to the substrate, higher wear and seizure resistance, higher fatigue strength due to the occurrence of compressive stresses on the surface, higher resistance to corrosion. The work discusses the properties of electro-spark deposited WC-Cu coatings subjected to laser treatment. The properties were established based on the results of a microstructure analysis, microhardness, surface geometric structure, adhesion tests and tribological properties. It is assumed that the use of laser-modified electro-spark deposited coatings will increase the applications of using relatively inexpensive materials in areas requiring special alloys, for example, sealing technology, precision products or surfaces in sliding contact.

The results presented in this article may be useful in other scientific areas, including by providing datasets for the development of analytical methods [9, 10], and information for improving techniques to strengthen the resistance of materials in environments that are chemically aggressive [11, 12], thermomechanically stressful [13] and exposed to biocorrosion [14-16]. In the industrial area, they can be used to improve the durability of machine parts by strengthening the surface layer [17, 18], modifying its resistance [19, 20] and performance properties [21, 22]. The experience gained may be an inspiration in the area of analytical [23-25] and organizational [26, 27] methodologies. It can also be useful when designing the structure of specific industrial databases [28, 29], as well as non-contact shaping techniques [30, 31].

2 MATERIALS AND TREATMENT PARAMETERS

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. An EIL-8A pulse spark generator was used to deposit the coatings on the steel surface. The operating parameters of the generator were determined experimentally: 0.7 A, 230

V and 150 μF capacitors. Cylindrical electrodes, 5 mm in diameter and 10 mm in height were used. They were produced by means of the impulse-plasma sintering method in a graphite matrix of tungsten carbide (particle diameter ~0,2 μm) and metallic copper (particle diameter ~0.04 μm) nanopowders at a temperature of 950 °C, under a pressure of 40 MPa. The nanopowders were mixed in the following proportions: 75% WC and 25% Cu, 50% WC and 50% Cu, 25% WC and 75% Cu. The following designations were given to the particular electrodes: WC25-Cu75, WC50-Cu50 and WC25-Cu75, Figure 1.

Then, the coatings were treated with an Nd:YAG laser (impulse mode) model BLS 720. The samples with electro-spark deposited coatings were laser-modified using the following parameters: spot diameter d = 0.7 mm, power P = 60 W, laser beam velocity v = 250 mm/min, nozzle-workpiece distance Δf = 6 mm, pulse duration t_i = 0.4 ms, pulse repetition frequency f = 50 Hz, beam shift jump S = 0.4 mm, nitrogen gas shield Q = 25 l/min.

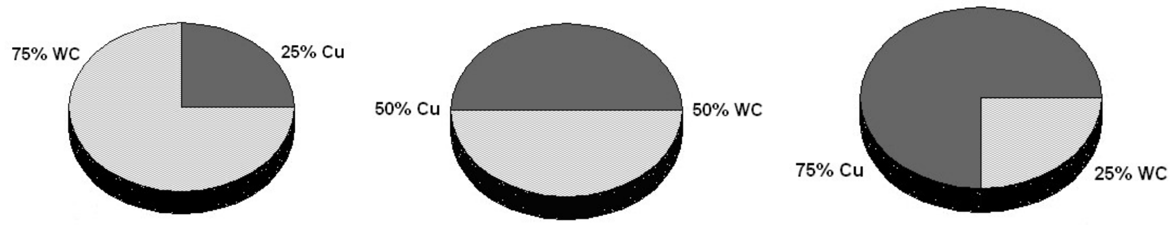


Figure 1: Composition of nanopowders mixture containing tungsten carbide and copper

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Microstructure analysis

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

In Figure 2a the microstructure of electro-spark deposited two-layer WC-Cu (WC50-Cu50) coating is presented. The layer thickness is approximately 36-40 μm, and the range of the heat affected zone (HAZ) inside the (underlying) substrate material is about 20-30 μm. In the photograph, the boundary line between the two-layer coating and the substrate is clearly visible. There are microcracks running across and along the coating. A linear analysis of the elements (Figure 2b) of the WC-Cu coating shows that the distribution of elements is non-uniform; there are zones with greater concentrations of W, Cu and Fe. Analyzing the linear distribution of elements, one can see that the adhesion of the coating to the substrate is of diffusive type.

The melting and solidifying processes during laser treatment resulted in the migration of elements across the coating-substrate interface. Laser radiation caused intensive convective flow of the liquid material in the melt pool and, in consequence, the homogenization of the chemical composition (Figure 3b). It also led to the structure refinement and highly saturated phase crystallization (Figure 3a) due to considerable gradients of temperature and high cooling rates. The technological surface layers, produced by laser alloying, were free from microcracks and pores (an effect of surface sealing), and non-continuities across the coating-substrate interface. No significant change in the chemical composition of the substrate was observed.

The thickness of the fused two-layer of the WC-Cu coating was in the 40-74 µm range. In the heat affected zone (HAZ), which was 30-45 µm thick (Figure 3b).

3.2 Measurements of the surface geometric structure

Surface geometric structure (SGS) is one of the main determinants of its quality. It has a significant influence on many processes occurring in the surface layer. The geometry of the surface is defined as the set of all inequalities resulting from the processes of material consumption. Operational data shows that approximately 90% of all manufacturing defects originate in the surface from various types of mechanical damage. One of the main disadvantages of the coatings produced by electro-spark deposition is high surface roughness. By reviewing the literature and analyzing the latest developments in this technology, one can notice that the surface generation process involves erosion of the base material and formation of microcraters and ridge by particles leaving the electrode. The surface is regular with rounded microroughness peaks. The effect of the process parameters on the formation of surface roughness has been described in numerous publications. By controlling these parameters, it is possible to obtain surfaces with pre-determined microgeometry. Electro-spark deposition allows for producing surfaces with enhanced roughness called surface relief.

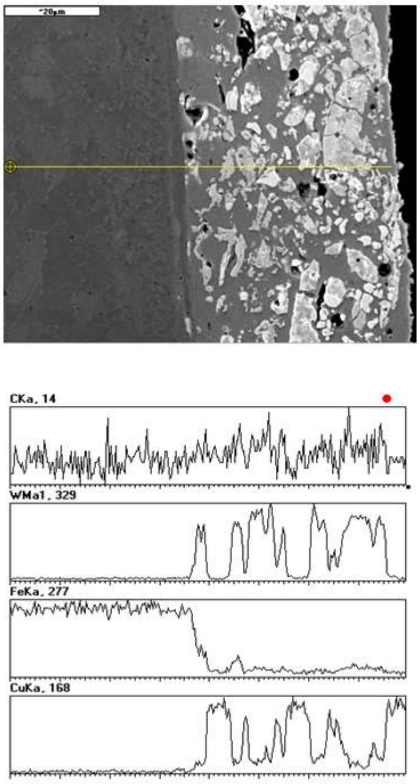
a)
b)


Figure 2: Microstructure (a) and linear distribution of elements (b) in the WC-Cu coating

a)
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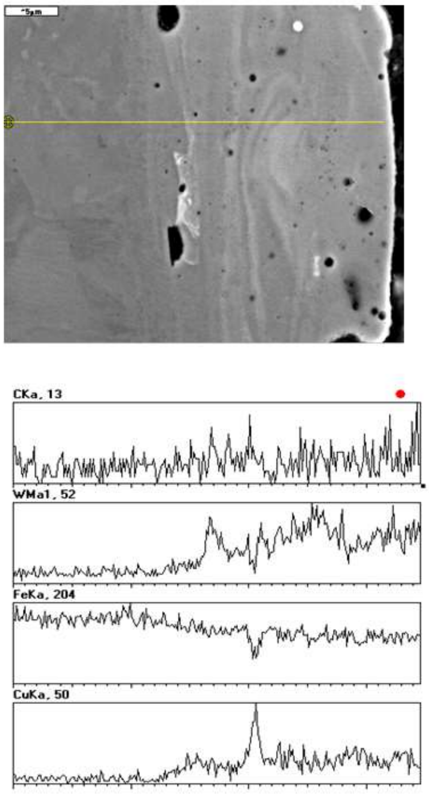

Figure 3: Microstructure (a) and linear distribution of elements (b) in the WC-Cu coating after laser treatment

The SGS of the WC-Cu coatings was measured at the Laboratory for Measurement of Geometric Quantities of the Kielce University of Technology using a TALYSURF CCI equipment. Three-dimensional surfaces and their analysis using the software TalyMap Platinium allowed us to know thoroughly the geometric structure of the surface tested.

Figure 4 presents an example three- dimensional surface topography measurement of the WC50-Cu50 coatings after and before laser treatment. Table 1 provides major parameters of the surface geometric structure of the examined specimens.

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 higher by almost 5% . Laser processing caused a slight decrease in the *Sa* parameter, which is very beneficial for surface quality.

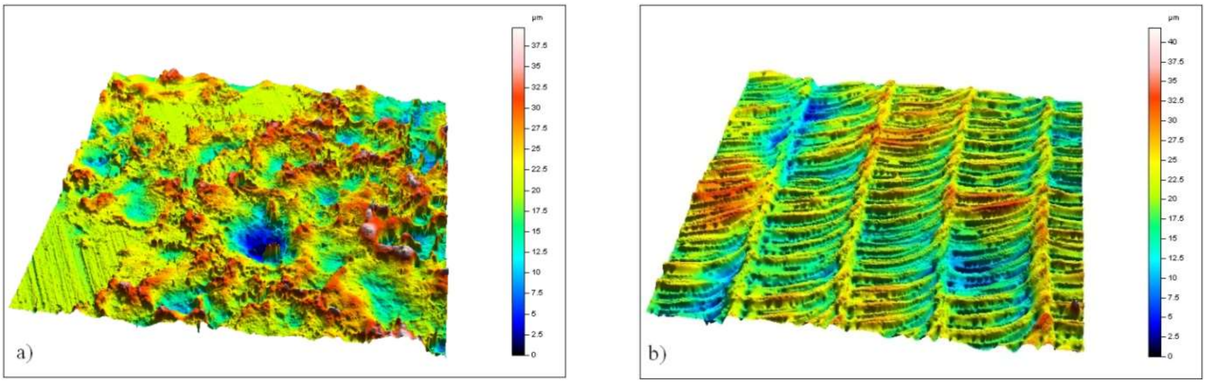

Figure 4: Specimen surface topography: a) before laser treatment, b) after laser treatment

Table 1: Parameters of the surface geometric structure

SGS parameters	Coating	
	WC-Cu	**WC-Cu + laser**
Sa (µm)	3.98	3.80
Sq (µm)	5.25	4.69
Ssk	-0.22	-0.28
Sku	3.87	2.70
Sp (µm)	18.20	12.89
Sv (µm)	21.52	18.96
Sz (µm)	39.73	31.86

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.

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.

3.3 Microhardness and adhesion tests

The microhardness was determined using the Vickers method (Microtech MX3 tester). The measurements were performed under a load of 0.4 N. The indentations were made in perpendicular microsections in three zones: the white homogeneous difficult-to-etch coating, the heat affected zone (HAZ) and the substrate. The test results for the electro-spark deposited WC-Cu coating before and after laser treatment are shown in diagrams in Figure 5.

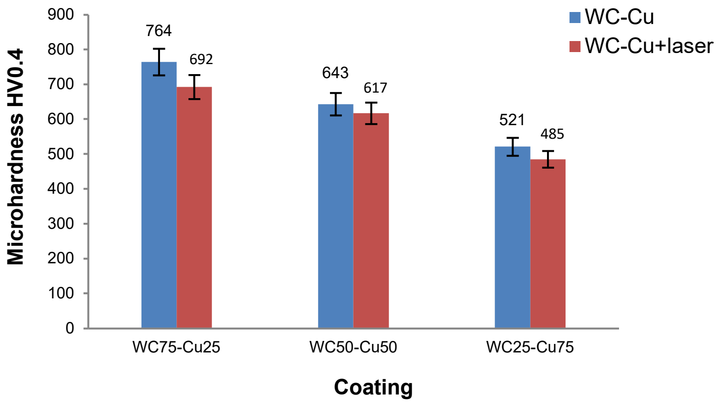

Figure 5: Results of the microhardness tests for the WC-Cu coating before and after laser treatment

Electro-spark deposition caused changes in the microhardness of the material. There was a considerable increase in microhardness after depositing the WC-Cu coatings. The microhardness of the substrate after electro-spark deposition was on average 278 HV0.4; the same value was reported for the substrate before the process. The microhardness of the WC-Cu coatings in the heat affected zone (HAZ) after the electro-spark treatment ranged from 58% to 63% and was higher than for the substrate material. The WC75-Cu25 coating had the highest microhardness both before and after laser treatment. The average microhardness of the WC75-Cu25 coating reached 764 HV0.4, and after laser treatment692 HV0.4. After using the WC25-Cu75 electrode, there was a clear decrease of microhardness to the level of 521 HV0.4. It is worth noting that the high content of copper in a WC-Cu coatings leads to a reduction of coating hardness, but at the same time it increases its flexibility, which is essential in improving the strength of some machine parts. The laser treatment of the ESD coatings caused a slight decrease in microhardness of both the coatings and heat affected zone. This fall may cause an improvement of their elastic properties, which is of significance during operation under big loads, as is the case of drilling tools in the extractive industry, or press elements in building ceramics. A scratch test was conducted to measure the adhesion of the WC-Cu coatings before and after laser treatment. A CSEM REVETEST scratch tester was used. The measurements were performed at a load increase rate of 39.8 N/min, a table feed rate of 1 mm/min and a scratch length of 5 mm.

The critical force was determined based on the records of changes in the acoustic emission signals and the tangential force as well as on the results of observations with an optical microscope fitted in the REVETEST tester. The values of the critical force were established by comparing the scratches left by the indentor with the responses of acoustic emission signals. Table 2 shows the values of the critical force obtained from three measurements of a given sample, the force mean values and standard deviations.

Table 2: Results of scratch adhesion tests

Coating	**Critical force (N)** Measurement number			**Mean value (N)**	**Standard deviation (N)**
	1	2	3		
WC75-Cu25	7.74	6.34	7.21	7.10	0.71
WC75-Cu25+laser	9.65	7.85	8.73	8.74	0.90
WC50-Cu50	8.67	7.93	9.12	8.57	0.60
WC50-Cu50+laser	10.71	12.06	10.94	11.24	0.72
WC25-Cu75	9.37	10.13	10.87	10.12	0.75
WC25-Cu75+laser	11.53	13.06	13.29	12.63	0.96

From the obtained data it becomes evident that due to laser treatment it is possible to markedly improve adhesion of the WC-Cu coatings to the C45 steel substrate. In addition, based on the results obtained, it can be stated that as the copper content increases, the coating's adhesion to the substrate increases. The WC25-Cu75 coating has the highest adhesion before and after laser processing. The mean value of the critical force of theWC25-Cu75 coating calculated from three measurements was 10.12 N; after laser treatment, it increased to 12.63 N. The laser treatment caused a 20% improvement in the adhesion of the WC25-Cu75 coating. In addition, the low scatter of critical stylus loads indicate that the laser treatment presumably eliminate voids present at the coating/substrate interface.

3.4 Tribological tests

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. 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. The WC25-Cu75 coating has the highest seizure load both before and after laser treatment. The mean value of the seizure load of the WC25-Cu75 coating calculated from five measurements was 6477 N; after laser treatment, it increased to 7563 N. The laser beam machining caused a 14% improvement in the adhesion of the WC25-Cu75 coating. The higher seizure load of coatings subjected to laser treatment was probably due to their lower porosity related to higher sealing properties. Further details, however, will be established in the next stage of the research. Analyzing Figure 6, it was found that as the copper content increases, the pressure load of the WC-Cu coatings before and after laser treatment increases.

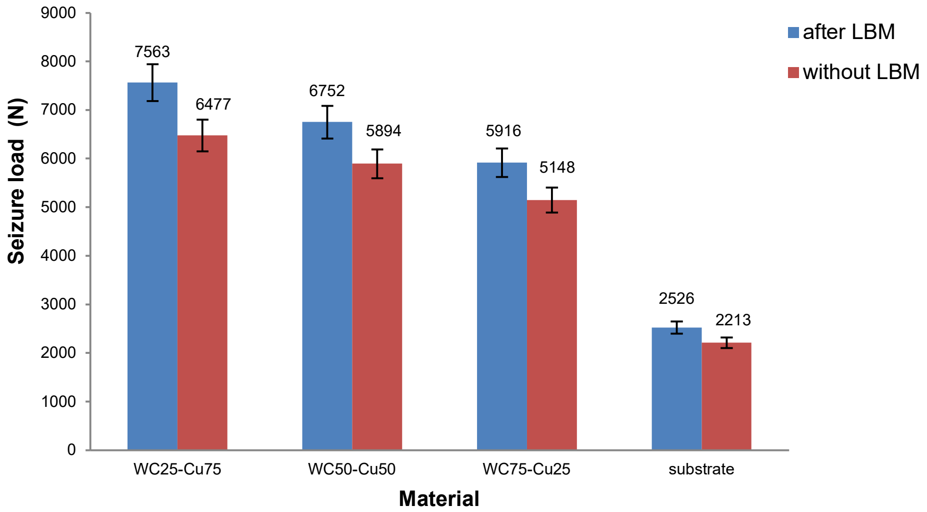

Figure 6: Average values of seizure load

4 CONCLUSIONS

The following conclusions can be drawn from the analysis and test results.

1. The surface of C45 carbon steel can be modified by means of electro-spark deposition using WC-Cu electrodes composed of various proportions of its two main constituents.
2. Concentrated laser beams can effectively modifying the state of the outer layer of ESD coatings thus changing their functional properties.
3. Laser irradiation of coatings resulted in the healing of micro-cracks and pores.
4. Parameters of surface geometric structure of the WC50-Cu50 electro-spark coatings have higher values when compared with SGS parameters of coatings after laser treatment.
5. Laser treatment of ESD WC-Cu coatings slightly reduces their microhardness.
6. Laser radiation causes an improvement in the functional properties of the electro-spark deposited WC-Cu coatings, i.e. they exhibit higher resistance to adhesion.
7. Laser processing of WC-Cu coatings increases by approximately 13-14% the load at which seizure occurs.
8. Further research should involve measurements of internal stresses and investigations into the erosion resistance tests of electro-spark coatings before and after laser beam machining.

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