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THE INFLUENCE OF LASER TREATMENT ON THE MICROSTRUCTURE AND PROPERTIES OF THE TUNGSTEN CARBIDE ELECTRO-SPARK COATINGS

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Summary

The aim of the study was to determine the influence of the laser treatment process on the properties of electro-spark coatings. The properties of the coatings after laser treatment were assessed based on following methods: microstructure analysis, adhesion tests, microgeometry measurement, microhardness tests and tribological studies.The tests were carried out on WC-Co coating (the anode) obtained by electro spark deposition over carbon steel C45 (the cathode) and molten with a laser beam. The coatings were deposited by means of the EIL-8A and they were laser treated with the Nd:YAG. The tests show that the laser-treated electro-spark deposited WC-Co coatings are characterized by lower microhardness and friction force, higher seizure resistance, roughness and adhesion. The laser treatment process causes the homogenization of the chemical composition, the structure refinement and the healing of microcracks and pores of the electro-spark deposited coatings. Laser treated electro-spark deposited coatings are likely to be applied in sliding friction pairs and as protective coatings.

Keywords: electro spark alloying, laser treatment, coating, wear

Wpływ obróbki laserowej na mikrostrukturę i właściwości powłok elektroiskrowych z węglika wolframu

Streszczenie

Określono wpływ obróbki laserowej na właściwości powłoki nanoszonej elektroiskrowo. Wykonano badania mikrostruktury, pomiary twardości, przyczepności i chropowatości powierzchni powłoki. Stosowano jako materiał powłoki WC-Co (anoda) nakładany elektroiskrowo na podłoże ze stali C45 (katoda). Wytworzoną powłokę przetapiano za pomocą lasera Nd:YAG. Powłoki WC-Co po obróbce laserowej charakteryzuje mniejsza twardość oraz większa chropowatość, przyczepność i odporność na zacieranie. Obróbka laserowa powoduje ujednorodnienie składu chemicznego oraz umożliwia usunięcie porów i mikropęknięć w materiale powłoki elektroiskrowej. Wytworzone powłoki po obróbce laserowej mogą być stosowane w ślizgowych węzłach tarcia lub jako powłoki ochronne.

Słowa kluczowe: obróbka elektroiskrowa, obróbka laserowa, powłoka, zużycie

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1. Introduction

Carbide coatings have numerous industrial applications. Characterized by high abrasion, sliding and erosion resistance, they can be used as a substitute for hard chrome plating.

Depositing protective layers on metal surfaces frequently involves matter and energy transfer, which is accompanied by various chemical, electrochemical and electrothermal reactions. To determine the operational properties of a surface layer, it is necessary to analyze the original, technological properties of the material, the deposition method, and particularly, the mechanism of energy accumulation inside and outside the workpiece [1].

By controlling polarity, it is possible to remove or replace material.

The process of material removal involving erosion of the stock subjected to electric discharges is called electrical discharge machining (EDM). The surface layer forming on the product improves its operational properties.

The process of material growth resulting from electroerosion is known as elektro-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.

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 [2]. Today, different electro-spark alloying techniques are used; they are suitable for coating formation and surface microgeometry formation [3-6].

Electro-spark alloying is becoming more and more popular as a surface processing technology. Electro-spark alloying coatings are frequently applied in industry, for example, to produce implants or cutting tool inserts. The coatings are deposited with manually operated equipment or robotized systems.

Coatings produced by electro-spark alloying are applied to:

- protect new elements,
- recover the properties of worn elements.

Electro-spark alloying coatings have some disadvantages, which can be easily eliminated. One of the methods is the laser treatment; where a laser beam is used for surface polishing, surface geometry formation, surface sealing or for homogenizing the chemical composition of the coatings deposited [7-10].

It is envisaged that the advantages of laser-treated electro-spark coatings will include:

- lower surface 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 the corrosion.

The aim of this study was to determine how laser treatment affects certain properties of electro spark alloyed WC-Co coatings. The properties of the coatings after laser treatment were assessed based on following methods: microstructure analysis, adhesion tests, microgeometry measurement, micro-hardness tests and tribological studies.

2. Experimental

In the experiment, the coatings were electro-spark alloyed using a WC-Co (97% WC and 3% Co) electrode with a cross-section of 3 x 4 mm – the anode – onto rings made of carbon steel C45 – the cathode.

The EIL-8A model was used as equipment for electro-spark alloying. Based on previous research and manufacturer recommendation, the following parameters were assumed to be optimal for ESA:

- voltage U = 230 V,
- capacitor volume C = 300 µF,
- current intensity I = 2.4 A.

In Figure 1 the electro-spark deposition equipment is illustrated.

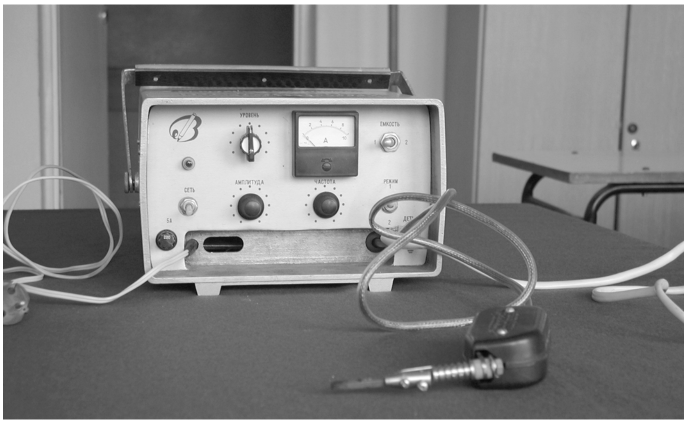


Fig. 1. View of EIL-8A – electro-spark deposition equipment

The quality of electro-spark deposition depends mainly on the shape, duration, and average value of current or pulse power. An average value of current is directly proportional to the number of generators operating in parallel.

Figure 2 shows a schematic diagram of a single pulse generator and following Fig. 3 presents current impulse shape from this device.

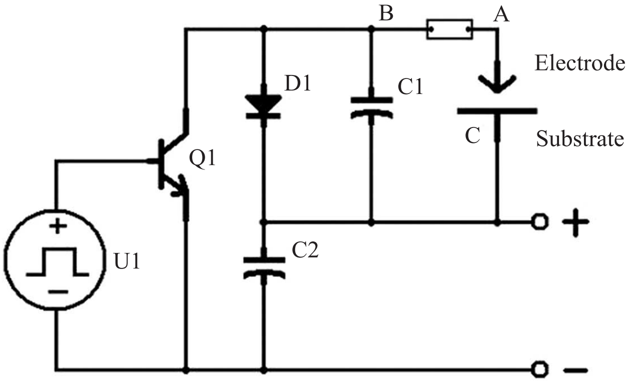


Fig. 2. Schematic diagram of a pulse generation system

Electrical energy stored in capacitor C2 is transmitted to the circuit: substrate – electrode in the form of a spark discharge and current flow. The process is initiated by switching on/of a transistor Q1. The switching frequency of the transistor is of the order of several to several dozen kHz. The capacitor C1 allows changing the shape and duration of an impulse as well as affecting the pulse-duty while setting pulse frequency of transistor Q1.

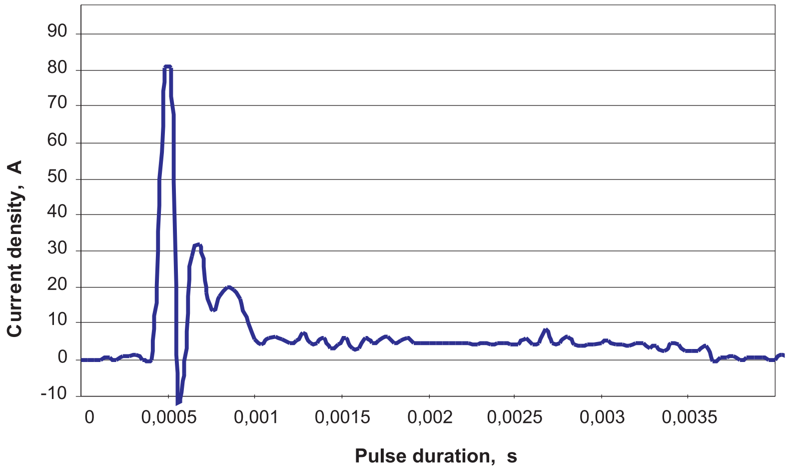


Fig. 3. Shape of a current impulse

Then, the coatings were treated with an Nd:YAG laser (impulse mode), model BLS 720. The samples with electrospark alloyed coatings were laser-modified with the following parameters:

- laser spot diameter: d = 0.7 mm,
- laser power: P = 20 W,
- traverse speed: v = 250 mm/min,
- nozzle-workpiece distance: Δf = 1 mm,
- pulse duration: ti = 0.4 ms,
- pulse repetition frequency: f = 50 Hz,
- laser beam shift jump: S = 0.4 mm.

3. Results and discussion

3.1. Analysis of coating morphology

A microstructure analysis was conducted for WC-Co coatings before and after laser treatment using a scanning electron microscope Joel JSM-5400. In Figure 4 selected view of the surface microstructure of an electrospark alloyed WC-Co coating is illustrated. From results obtained, it is clear that the thickness of the obtained layers was 20 to 30 μm, whereas the heat affected zone (HAZ) ranged approximately 15 to 20 μm into the substrate. In this micrograph (Fig. 4) there is a clear boundary between the coating and the substrate, where pores within microcracks are observed. The electrospark alloyed WC-Co coatings was modified via laser beam solidification, which caused their composition changes. The laser treatment leads to the homogenization of the coating chemical composition, structure refinement, and crystallization of supersaturated phases due to the occurrence of temperature gradients and high cooling rate.

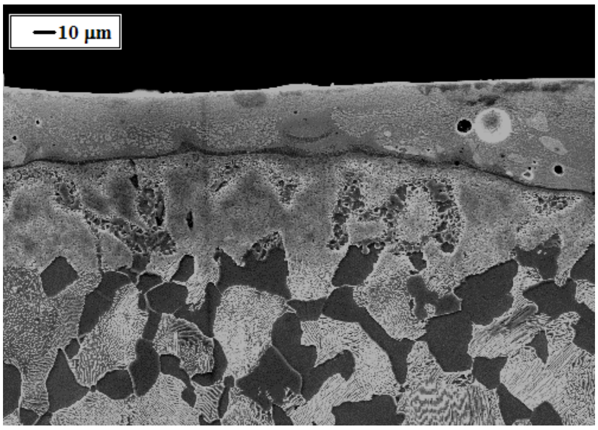


Fig. 4. WC-Co coating microstructure after electrospark alloying

The laser-modified outer layer does not possess microcracks or pores (Fig. 5). There was no discontinuity of the coating-substrate boundary. The thickness of the laser-treated WC-Co coatings was in the range of 40 to 50 μm. Moreover, the Heat-Affected Zone (HAZ) was in the range of 30 to 40 μm, and the content of carbon in the zone was higher.

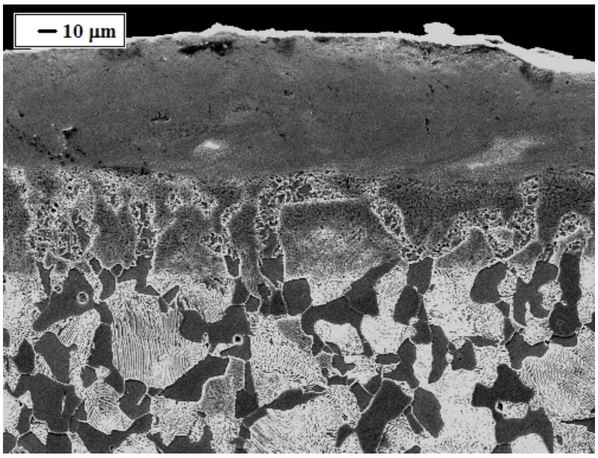


Fig. 5. Microstructure in the electrospark alloyed WC-Co coating after treatment with an Nd:YAG laser

3.2. Hardness tests

The Vickers method under a load of 0.4 N (40 G) was employed to analyze the microhardness of the coatings. The cross-sections of the metallographic specimens were done parallel in three zones to the: coating, fusion zone, and HAZ. The original material was also tested. In Figure 6 the microhardness test results concerning the WC-Co coatings before and after treatment are presented. The electrospark alloying process caused some changes in the material.

The average microhardness of the substrate after ESA was 142 HV0.04, which was the same as the initial state. The microhardness increase was achieved by deposited WC-Co coating via ESA method. The microhardness was higher than substrate material. The average microhardness of the WC-Co coating was 617 HV0.04. It was characterized by 335% increase compared to the substrate material. The HAZ microhardness after laser treatment was increased by 185% in relation to the substrate material. It was observed a slight decrease, about 21%, in the electrospark alloyed coatings microhardness after applied laser treatment. This fall may cause an improvement of their elastic properties, which is important during operation under big loads, e.g.: drilling tools in the extractive industry, or press elements in building ceramics.

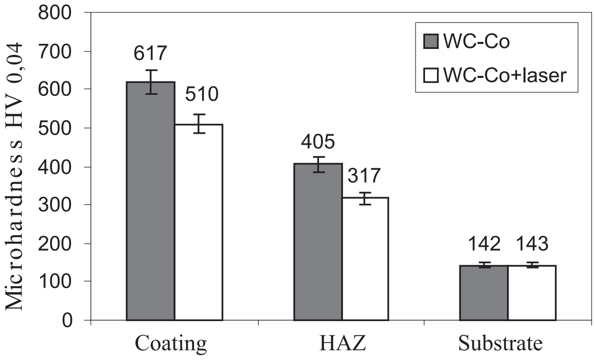


Fig. 6. Results of hardness measurements

3.3. Tribological studies

The tribological studies concerning the electrospark deposited coatings were carried out using a pin-on-disc tester, T-01M. In Figure 7 the T-01M principle of operation scheme is shown. In the test the friction force is measured for a predetermined load. The pin ϕ 4x20 mm was made of tool steel NC6. The samples and antisamples were prepared in accordance with the instruction [11]. The tests were conducted at the following friction parameters:

- rotational speed: n = 637 rev/min,
- number of revolutions: i = 5305 rev,
- test duration: t = 500 s (up to stabilization determined in the initial tests),
- range of load changes from 5 to 15 N.

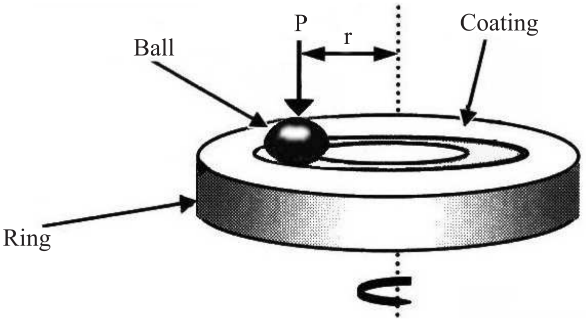


Fig. 7. Operation of the pin on disc type tester

In Figure 8 friction forces in the function of time and load of 10N is presented. For WC-Co coating before and after laser beam modification. In the case coatings dry friction was observed, which results in the transformation of the outer layer into a surface layer. This phenomenon was mainly due to the sliding stresses and speed, and the interaction with the medium. The state stabilization of the antiwear surface layer was observed.

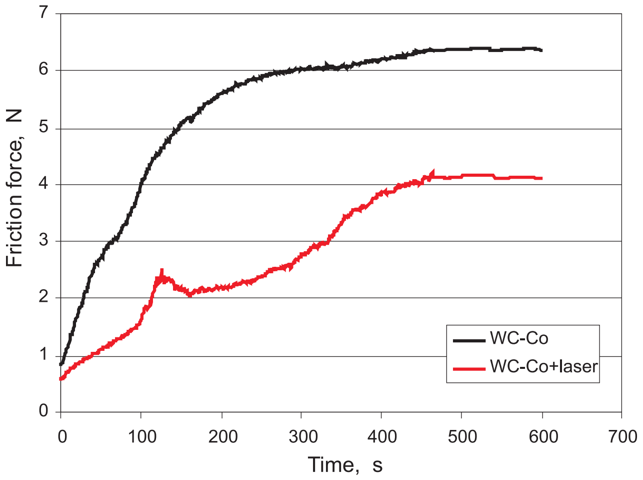


Fig. 8. Relationship between friction force and time

In Figure 8 the relationship between friction force and time is presented. It was observed that the stabilization of the friction force was achieved after 280 s. Before stabilization fluctuation from 6 to 6.2 N value was visible. In the case of a laser modified WC-Co coating, the friction force stabilizes after 400 s. Before stablization fluctuation from 3.9 to 4.1 N value was noted. The average friction force of a WC-Co coating was approx. 35% higher than laser-modified WC-Co coating (at the moment of stabilization). The difference in the coefficients of friction was similar.

Seizure resistance was measured using a T-09 pin on disc tribotester. Two prisms and a roller constituted the friction pair. The surfaces tested were WC-Co coatings an C45 steel before and after laser processing. The roller had a diameter of 6.3 mm was made of carbon steel. The tests were conducted for three kinematic pairs for each material variant, so it was possible to average the data. The experiment involved submerging the specimens in pure lubricant. In this case paraffin oil was used. This oil guarantees constant lubricating ability in each test carried out. It’s difficult to compare results, when lubricant oil with additional oilness improvers is applied. Some of improvers are biodegradable and are changing oil properties even during short time of storage. To obtain stable and comparable results parafin oil is commonly used in laboratory wearing tests. In Figure 9 an average seizure loads before and after laser processing is presented. It is clear that the laser processing operation caused an increase in the load force and accordingly, seizure of the electrospark deposited coatings and C45 steel.

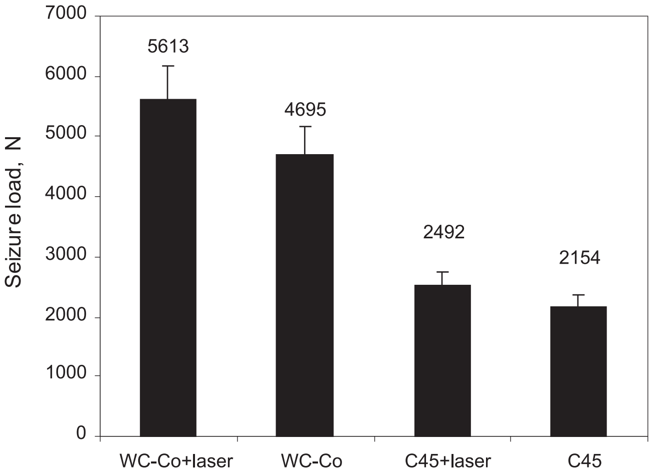


Fig. 9. Average seizure load

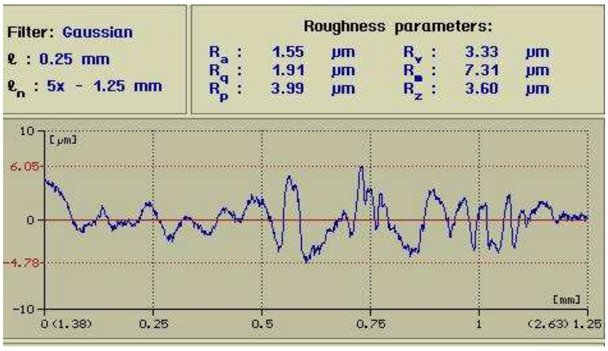
3.4. Microgeometry measurements

The roughness of WC-Co coatings was measured in two directions, which were perpendicular to each other. One measurement was performed in the direction of the electrode motion, the other perpendicular to the scan paths. The average value of roughness (parameter Ra) was calculated from the two measurements.

The roughness of the WC-Co coatings after laser treatment was determined in the directions perpendicular and parallel to the axis of the paths produced with a laser beam. The average value of roughness was calculated for each coating. Literature review shows that roughness profiles are usually measured along paths produced by a laser beam and the results do not reflect the real microgeometry of a surface after laser treatment. The maximum roughness heights are reported to occur in the direction perpendicular to the axis of the paths.

The roughness of the analyzed WC-Co coatings was in the Ra range from 1.55 to 2.07 μm. After laser treatment Ra was from 2.81 to 3.97 μm. The coatings deposited on steel specimens (C45) had Ra roughness from 0.36 to 0.38 μm. Figures 10 and 11 presents an example microgeometry measurement protocols.

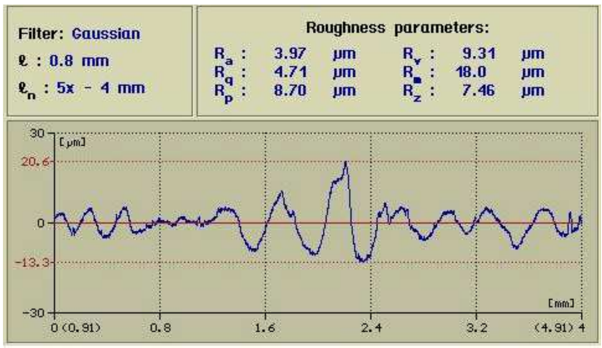
From the measurement results it is clear that there is an increase in the roughness of the WC-Co coatings after laser treatment. The higher roughness resulted from the tensile forces acting on the surface, and accordingly, the motion of the liquid metal. A non-uniform distribution of temperature in a laser beam (Transverse Electro Magnetic mode TEM_{00}) caused the non-uniformity of the surface profile after solidification, which reflects, to some extent, the distribution of energy in the melted zone.



Filter: Gaussian
ℓ : 0.25 mm
ℓ_n : 5x - 1.25 mm

Roughness parameters:
R_a : 1.55 µm
R_q : 1.91 µm
R_p : 3.99 µm
R_v : 3.33 µm
$R_{\blacksquare}$: 7.31 µm
R_z : 3.60 µm

Fig. 10. Surface roughness of the WC-Co coating deposited



Filter: Gaussian
ℓ : 0.8 mm
ℓ_n : 5x - 4 mm

Roughness parameters:
R_a : 3.97 µm
R_q : 4.71 µm
R_p : 8.70 µm
R_v : 9.31 µm
$R_{\blacksquare}$: 18.0 µm
R_z : 7.46 µm

Fig. 11. Surface roughness of the WC-Co coating
after laser treatment

If pulse laser treatment is applied, it is assumed that the main factor affecting the surface profile after solidification is the pressure of vapour causing the disposal of the material from the central zone and the production of characteristic flashes on the boundary between the melted and unmelted zones.

3.5. Adhesion tests

A scratch test was conducted to measure the adhesion of the WC-Co coatings before and after laser treatment. A CSEM REVETEST scratch tester was used. The measurements were performed at a load increase rate of 103.2 N/min, a table feed rate of 9.77 mm/min and a scratch length of 9.5 mm.

A special indenter – a Rockwell diamond cone with a corner radius of 200 µm, was used to scratch the samples at a gradually increasing normal force (load). The information about the cracking or peeling of layers was obtained basing on the measurements of the material resistance (tangential force) and the recording of acoustic emission signals. The lowest normal force causing a loss of adhesion of the coating to the substrate is called critical force and is assumed to be the measure of adhesion.

The critical force was determined basing 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 indenter with the responses of acoustic emission signals. Table 1 shows the values of the critical force obtained from three measurements of a given sample, the force mean values and standard deviations.

Table 1. Results of the adhesion test

Coating	**Critical force, N**			**Mean value, N**
	measurement number			
	1	**2**	**3**	
WC-Co	6.23	6.17	5.56	5.99
WC-Co+laser	7.84	8.24	7.57	7.88

Laser-treated coatings produced by electro-spark alloying are reported to possess adhesion higher than untreated coatings. The mean value of the critical force of the WC-Co coating calculated from three measurements was 5.99 N; after laser treatment, it increased to 7.88 N. The treatment caused a 32% improvement in the adhesion of the WC-Co coating. The higher adhesion 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.

Conclusion

After the carried out investigations, the following conclusions can be drawn:

- The electrospark alloyed coating outer surface layer could be modified via focused laser beam, which has significant impact on the coating surface properties.

- The laser treatment causes that the electrospark alloying coatings melt and then solidify. The refinement of structure and disappearance of microcracks were noticed.
- The friction force average value (at the moment of stabilization) reached during the tribological tests for a WC-Co coating was approximately 35% higher than that obtained for the same coating after laser modification.
- After laser processing significant load force can be applied. The material seizure of the WC-Co coatings modified after laser treatment was increase about 16%.
- Laser treatment caused a 21% decrease in the microhardness of the electrospark alloying WC-Co coatings.
- After laser treatment, the roughness of the electrospark deposited coatings almost doubled. This phenomenon is unfavorable if the quality and applicability of the coatings under certain service conditions are to be considered. It is essential to determine which parameters of laser treatment cause the melting of the coating microroughness peaks (laser smoothing).
- Laser treatment caused a 32% increase in the adhesion of the electrospark alloying WC-Co coatings.
- The further research will extend measuring investigations for residual stresses and porosity of electrospark WC-Co coatings before and after laser treatment.

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