New variants of the overlaying processes

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1. Introduction

Overlaying is applied for realizing surfaces with special properties on various parts of industrial and energetic equipment and installations. In this paper, a few new variants of overlaying processes are analyzed, that belong to three main classes: surfacing by welding or cladding, thermal spraying and electro-spark coating. These are also ecological technologies with no toxic substances, as used in electroplating processes.

2. Surfacing by welding

Surfacing is a welding process used to apply a hard, wear-resistant layer of metal to surfaces or edges of worn-out parts. It is one of the most economical methods of conserving and extending the life of machines, tools, and construction equipment. Surfacing is often used to build up worn shafts, gears, or cutting edges. A main characteristic is the very good adherence of the overlay to the base metal.

2.1. Cold metal transfer (CMT)

There are some materials and applications where having only a low thermal input is extremely beneficial. It is possible,

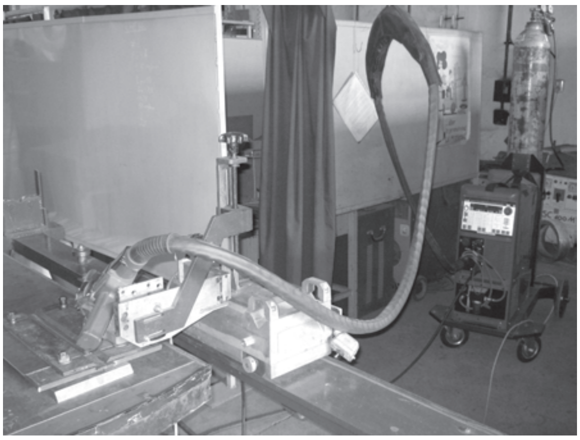

Figure 1. Equipment for cold metal transfer (CMT) welding and surfacing [2].

for example, to weld seams without root-side drop-through, to perform spatter-free brazing, as well as to make certain difficult types of joints. The word "cold" has to be understood in terms of a welding process, with a relative meaning. But when compared to the conventional MIG/MAG process, CMT is indeed a cold process. This is an alternating hot & cold treatment that has been made possible by a new technological development [1, 2]. And above all, by incorporating the wire motions into the process-control. The result is spatter-free MIG/MAG welding and brazing for ultra-light gauge sheets from 0.3 mm (0.012"), in either automated or manual applications. The process is also applied for cladding with low dilution.

2.2. Laser hybrid processes

A conventional weld process clad dilution zone is measured in fractions of a millimeter or even in millimeters; a laser process dilution zone is measured in microns.

This is exactly what makes powder laser cladding so attractive [3]. A mature though not widely adopted technology, this process uses a laser to melt powder and create a clad with a thin, strong metallurgical bond (or dilution zone) with the base metal on the order of 100 microns (see Figure 2). This makes for a near chemically pure clad that is ideal for corrosion resistance. Ductile deposits as thin as 1.27...25.4 mm were made in materials that would generally be considered unweldable. Unique material properties can be achieved with custom matrix composites using the rapid melting and quenching of laser processing.

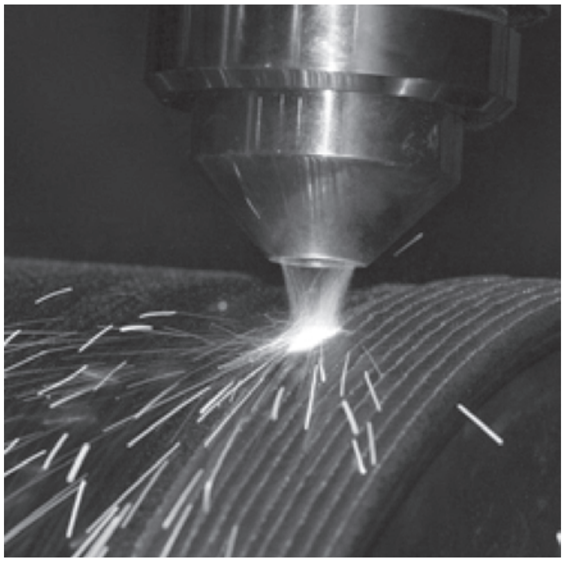

Figure 2. Laser-powder cladding [3].

Solid-state lasers, including direct diode and fiber varieties are used. These have shorter wavelengths than CO_2 laser beams, so the metal can better absorb the energy.

Powder is delivered through one of several types of heads. Most common is the coaxial powder laser head in which the powder nozzle surrounds the laser beam. One type has a lateral nozzle. Other variants have scanner laser heads that move a spot extremely quickly to form a line, circle, oval, or other shape. These lasers are used with a line nozzle that delivers a band of metal powder roughly 15 mm wide.

There are some limitations of the process. First, most of the efficient powder delivery systems cannot defy gravity, so the laser and nozzle usually need to be positioned above the workpiece. Second, the surface texture may be a little rough, because some powder grains fall into the pool as it cools. Third, some powder does not enter the pool, only 90% of the powder are used.

2.3. Hot-Wire Laser Cladding

The hot-wire process [3] combines preheated GMAW wire with a multi-kilowatt, solid-state, fiber-delivered laser (Figure 3). This kind of laser cladding also produces a microns-thick dilution zone between the base and clad metal (with nearly chemically pure clad) and offers increased deposition rates. The deposition rates in production are in the range 0.89 – 1.33 kg/hour.

The GMAW power source is software-based synchronized with the laser. It heats the wire in short circuit connection, without any electric arc. The preheated wire, which feeds at a specified angle to the laser beam, reduces the power requirements from the laser. The process is similar to powder-laser cladding and with the advantages of using a wire, cheaper than powder.

Figure 3. Hot-wire laser cladding [3]
(laser head out of the frame).

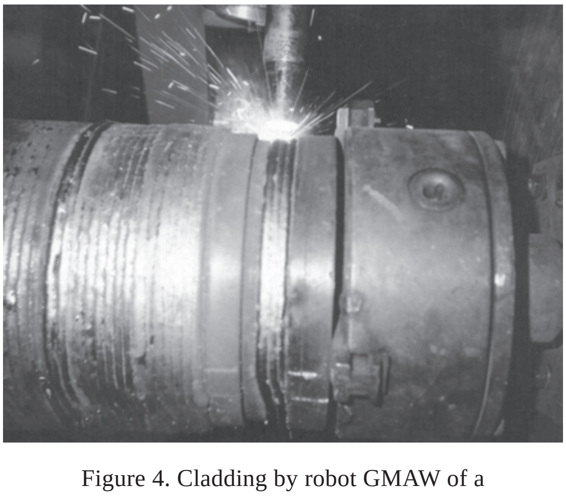

Figure 4. Cladding by robot GMAW of a
rolling stock cylinder [9].

This process was applied for making a thick clad of 600-series Inconel alloy, for possible applications in the oil and gas industry, instead of pipe cladding by hot-wire GTAW.

2.4. Cladding with flux cored wires

Gas-shielded and self-shielding flux-cored wires are generally intended for hardfacing mild and low-alloy steel components prone to moderate abrasive wear and medium to high impact.

The deposits have a wide range of hardness of 30...60 HRC, depending on the chemical composition of the wire, that can have plenty of variants [4-8]. They are suited for build-up or overlay operations and can be used for multiple- layer deposits. Their target is lengthening of part life and preventing excessive wear.

In Figure 4, cladding by robot GMAW of a rolling stock cylinder, performed at ISIM of Timisoara, using flux-cored wire, is presented [9].

3. Thermal spraying

Thermal spraying is a class of coating processes in which melted or plastified materials are sprayed onto a surface. The filler material is heated by electrical (plasma or arc) or chemical means (combustion flame). The basic steps of a thermal coating process are: substrate preparation; masking and fixturing; coating application; stripping; finishing.

The basic parameters are: particle's temperature, velocity, angle of impact, and amount of reaction with gases during the deposition process. Coating quality is usually assessed by measuring its porosity, oxide content, macro and micro-hardness, bond strength and surface roughness. Generally, the coating quality increases with increasing particle velocities. Several industries use thermal spray as a substitute for plating.

3.1. Plasma spraying with remelting

At ISIM of Timisoara, experiments for depositing microlayers from ceramics were performed [10-12]. The combinations of oxide ceramics based on ZrO_2, Cr_2O_3, Al_2O_3, doped with Y_2O_3, TiO_2, SiO_2, CaO and MgO were chosen. The plasma jet arc [12], as a variant of the plasma thermal-spraying was applied, with the versions A, B, C, D, E. The substrate are titanium alloys. The granulation of the powder is 15...65 µm. The overlays have been remelted with concentrated energy beams (electron and laser).

The parameters of the thermal spraying process are in the ranges: Current I_s = 500 A; Voltage U_a = 58...70 V; Spraying distance d_s = 58...70 mm.

The parameters of the remelting with electron beam are: Voltage U_{acc} = 60 kV; Current I_{fs} = 20...30 mA; Work distance D_{tr} = 150mm.

By the remelting with laser beam, the parameters are: pulse time d_p = 0.60 ms; frequency f = 34 Hz; pulse power 3800...4600 W.

For the spraying time of 15 sec., the average thickness of the microlayers is in the range 52.30...72.50 µm, with a mean square deviation of 2.66...4.39 µm.

3.2. High velocity oxygen-fuel process

With high-velocity oxy-fuel (HVOF) systems, the powder is heated to near or above its melting point and is deposited by a high-velocity combustion gas stream. The most utilized fuels are propane, propylene or hydrogen. Some applications are worn parts reclaiming and machine buildup, seals, ceramic hardfacings, jet engine components, etc.

This technique has high-velocity impact. Coatings applied with HVOF exhibit little or no porosity. Deposition rates are relatively high, and the coatings have acceptable bond strength. Coating thicknesses range from 0.000013 to 3 milimeters. Some oxidation of metals or reduction of oxides can occur, with quality effect.

The paper [13] presents the obtaining mode of titanium nitride layers by depositing titanium nitride powder (-15 + 5 µm) using High Velocity Oxygen Fuel Thermal Spraying Process (HVOF) on titanium alloy substrates (Ti_6Al_4V), with the parameters presented in the table 1.

Table 1. HVOF thermal- spraying parameters [13].

Parameter	Value
Oxygen [l/min]	300
Hydrogen [l/min]	90
Kerosene [l/h]	2.5
Carrier gas [l/min]	15
Deposition rate [g/min]	15
Spraying distance [mm]	60; 70; 80

4. Electro-spark deposition

This process replaced the detonation-gun or HVOF processes and provided orders of magnitude increase in wear and damage resistance, a five-fold improvement in corrosion performance, lower friction, and more than a 50% saving in cost, with the same material. The process was in production of nuclear components for 10 years, with no failure or reject [14].

Electro-spark Deposition (ESD) is a micro- welding process, which uses electrical pulses frequencies in the 0.1 to 2 kHz range and thus allow substrate heat dissipation over ~99% of the duty cycle while heating only ~1%.The result is cooling rates of 105 to 106 °C/sec, and generation of nano-structures, amorphous for some alloys, with corrosion and tribological benefits. This also eliminates thermal distortions.

The ESD are among the most damage-resistant coatings, suitable for high stresses, high temperatures, thermal cycling, irradiation, wear, corrosion, and erosion. An applications is the three-times increase in life of high-speed steel milling cutters after ESD with tungsten carbide. Other application are: ship propeller components, casting moulds, fuel supply system parts, exhaust system components, implants or cutting tools.

The ESD coating is realized in an environment of local high temperature and pressure [14,15]: shock wave pressure from the electric spark (2...7)•10^3 GPa; temperature (5...40)•10^3 °C. Deposition times are several minutes per cm^2.

4.1. ESD of tungsten carbides

The work presented in [16] determines the influence of the laser treatment process on the properties of electro-spark coatings. The studies were conducted using WC-Co-Al_2O_3 electrodes produced by sintering nano-structural powders.

In another experiment, the coatings were realized by electro-spark process, 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) [17, 18, 19].

The EIL-8A model was used as equipment for ESD, with the following parameters:

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

The quality of electro-spark deposition depends mainly on the shape, duration, and average value of current or pulse power. Then, the coatings were treated with an Nd:YAG laser (impulse mode), model BLS 720, 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: D_f = 1 mm,
- pulse duration: t_i = 0.4 ms,
- pulse repetition frequency: f = 50 Hz,
- laser beam shift jump: S = 0.4 mm.

4.2. ESD on spot welding electrodes [20]

To improve the electrode life for resistance spot welding (RSW) of Zn-coated steel sheets, coatings of a special alloy TiCP/Ni were deposited unto the electrode surface, by the electro-spark process, followed by laser treatment.

4.3. Experimental model

ISIM of Timisoara has contrived and realized an experimental model for electro-spark coating, shown in Figure 5 [21]. Electro-spark coatings were performed using a stainless steel electrode

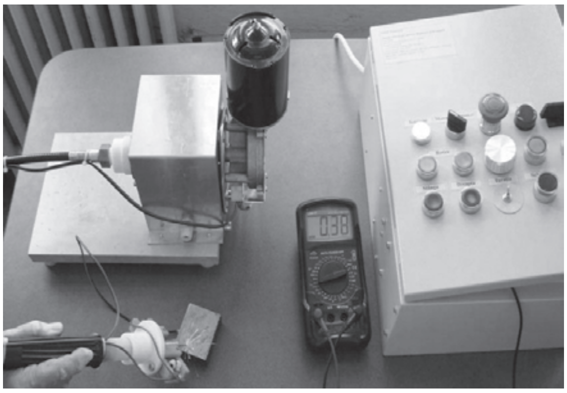

Figure 5. Device for electro-spark coating [21].

Ø2,5mm. In 10 min, a coating of about 10mm x 12mm and 0.05...0.10 mm thick can be made.

5. Results and discussion

5.1. Plasma spraying with remelting

5.1.1. Structure and mechanical characteristics

By the microscopic examination, according to EN1321:2003, the following micro-structures were detected for the plasma spraying [12]:

A) solid solution (Zr, Y), fine particles of unsolved oxides of Zr and Y, respectively Ti particles of different shapes, having the hardness 306...495HV1, according to EN ISO 6507-1:2006.

B) hybrid structures made of ternary solid solutions (Cr, Si, Ti), fine particles of unsolved oxides of Cr, Si, Ti and non-uniform titanium particles, with the hardness 362...741 HV1.

C) structures made of binary solid solutions based on Zr and Ca, with unsolved, fine particles of Ti; the hardness is 353...686 HV1.

D) structures made of binary solid solutions of Zr and Mg oxides, with zones of compounds MgO_2 and ZrO_2, with fine, non-uniform particles of Ti, having the hardness 418...677 HV1.

E) structures made of solidified alumina (Al_2O_3), fine particles of lower oxides of Al, with fine particles of Ti; the hardness is 400...772 HV1.

The depositions made with laser beam have higher extents of the hardness, due to the higher cooling rate, and most of the structures are acicular. A local hardening estimator AHV1 can be calculated by the relationship:

$$\Delta HV1 = (\Delta HV1_{Max} - \Delta HV1_{min})/\Delta HV1_{Max} \bullet 100[\%] \quad (1)$$

where $\Delta HV1_{Max}$ is the maximum in one zone and $\Delta HV1_{min}$ is the minimum hardness in another zone. The estimator is less than 50%, which means that there is no strong local hardening.

5.1.2. Cavitation erosion test

The cavitational erosion test was made on special specimens in a magnetostrictive station, having the characteristics [12]:
- immersion depth of the sample: 3...5 mm;
- oscillation frequency 7,000 Hz;
- oscillation amplitude: 47 µm;
- work environment: good water, at +20°C;
- atmospheric pressure;
- test duration: 165 min, in stages of 5...15 min.

Examination by scanning electron microscopy (SEM) of the section of the samples evinces a mechanical cold hardened layer, different compounds and other brittle phases, cohesionless to the base matrix. Also, on the surface of the covering microlayer, damaged by the cavitation bubbles implosion, there are many microholes with diametres of 3...6 mm. Because the ceramic microlayer has high mechanical resistance and hardness (677 HV1), there are no strong yielding processes, only an increase of the dislocations density, with formation of cracks and possible propagation of fracture by fatigue.

The cavitational erosion rate v_{erc} can be calculated with the equation (2):

$$v_{erc} = \Delta G / t \quad (2)$$

where ΔG is the weight loss, related to the previous extent, mg; t is the test duration, min.

The values of the cavitational erosion rate v_{erc} are in the range 0.012 (version A)...0.900 mg/min (version D). There is a tendency of increase of the v_{erc} in the first periods of testing, by the version D.

The lowest values of v_{erc} have been obtained with the samples remelted by laser beam. The coating of ZrO_2 doped with ceramic oxides has a good behaviour to cavitation erosion.

The slow degradation of the ceramic microlayers show their lower sensitivity to mechanical cold hardening phenomena.

5.1.3. Dry friction wear test

The samples with microlayers are cylindric and bevelled, with the sizes 30 x10 mm.

Every sample was subjected to the test, on the equipment MTU, with the parameters [12]:
- applied force: 15 daN;
- axle speed: 400 rpm;
- time of wear cycle: 30 hours.

The weight loss ΔG was determined for every sample. These extents are in the range 0.166... 0.452 g (version D). The total time of the wear test is 140 hours. The variation of the weight loss depending on the wear time was represented.

5.2. HVOF spraying

Figure 6 shows the micro-graphs of the deposited TiN layers, at 4000x magnification, obtained by scan electron microscopy (SEM) [13].

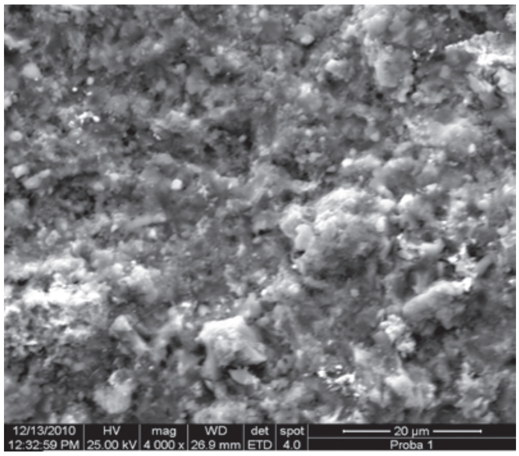

Figure 6. SEM analysis of titanium nitride layer deposited by HVOF thermal spraying, 4000x [13].

The variation of the thickness of the TiN coating is shown in the histograms of the Figure 7.

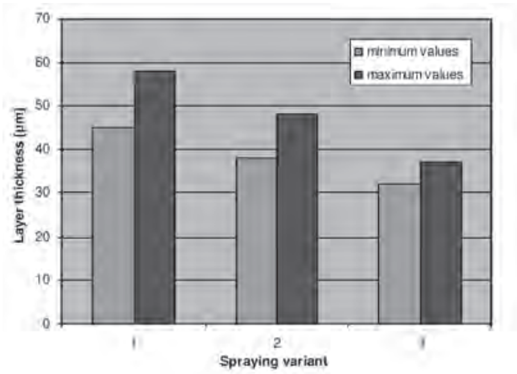

Figure 7. Thickness of the HVOF coating [13].

Due to the relatively low temperatures of HVOF thermal spraying process, the deposited layers of TiN on Ti alloy have a relatively low level of oxides and no defects, as cracks or peeling.

5.3. Electro-spark deposition

5.3.1. Analysis of the coating morphology

A micro-structure analysis was conducted for the WC-Co coatings [17], using a scanning electron microscope Jeol JSM-5400, before and after the laser treatment.

The thickness of the ESD obtained layers was 20 to 30 µm, whereas the heat affected zone (HAZ) ranged 15 to 20 µm into the substrate. There is a clear boundary between the coating and the substrate, where pores within micro-cracks are observed, as shown in the Figure 8.

The laser treatment leads to the homogenization of the chemical composition, structure refinement, and crystallization of supersaturated phases, due to the occurrence of temperature gradients and high cooling rate. The laser-modified outer layer has no micro-cracks and pores and no discontinuity of the coating-substrate boundary, as presented in the Figure 9. Its thickness was in the range of 40 to 50 µm. The HAZ thickness was 30 to 40 µm. Its content of carbon was higher.

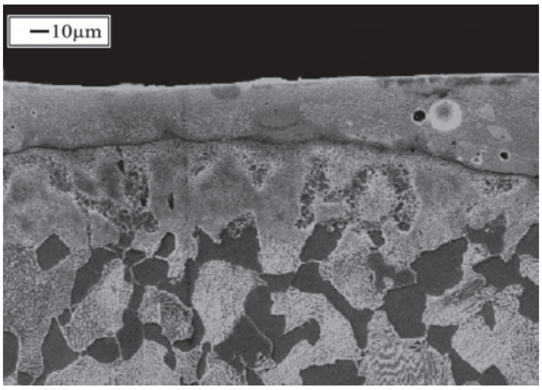

Figure 8. WC-Co coating microstructure after the electro-spark coating process [17].

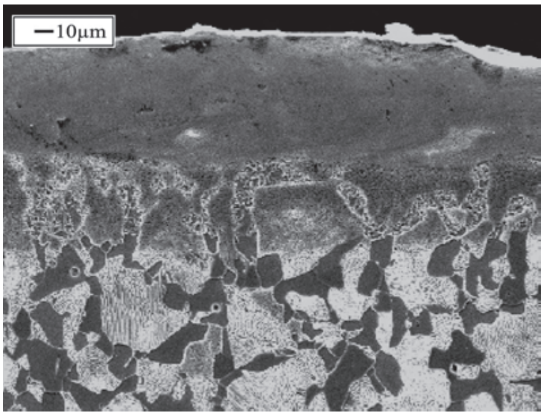

Figure 9. Microstructure in the electro-spark WC-Co coating after treatment with a Nd:YAG laser [17].

5.3.2. Hardness tests

The average micro-hardness of the substrate was 142 HV0.04, as previously. The average micro- hardness of the WC-Co coating [17] was 617 HV0.04, that is a 335% increase compared to the substrate. The HAZ micro-hardness after laser treatment has increased by 185% in relation to the substrate. A slight decrease of 21% of the coating micro-hardness after the laser treatment occurred, that may cause an improvement of the elastic properties, which is important for operation under high loads, e.g.: drilling tools in the extractive industry, press elements for ceramics [17], etc.

5.3.3. Tribological studies

The tribological studies [17-19] were carried out with a pin-on-disc tester, T-01M. The pin of 4x20 mm was made of tool steel NC6. 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.

Dry friction and status stabilization of the anti- wear layer was observed. The average friction force was 35% lower after the laser treatment.

Seizure resistance was measured using a T-09 pin on a disc tribotester. In the Figure 10 average seizure loads before and after laser processing are presented. The laser processing caused an increase in the seizure of the coatings and C45 steel.

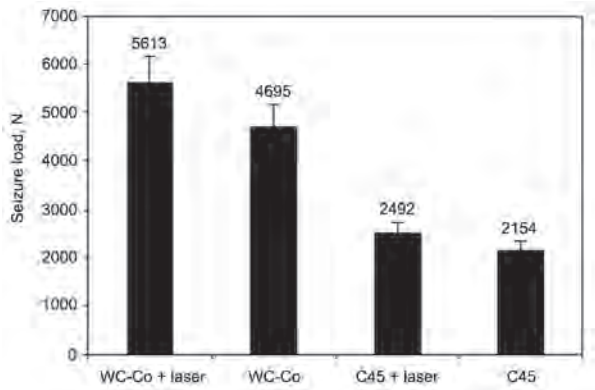

Figure 10. Average seizure load [17].

Other research on electro-spark deposition is conducted at NASA and US Navy [14].

5.3.4. 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 mean value of the critical force 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, probably due to the lower porosity and higher sealing [17].

Recent research [22] has demonstrated the possibility of surfacing by friction stir welding FSW, with consumable tool made of advanced materials (alloys of Al, Mg, Ti, Cu), with good adherence, on steel surfaces, for improving their functional proprieties.

5.3.5. Pitting erosion of the coating

As resistance welding tests have shown, with Ni/(TiCP/Ni)/Ni coating on the electrode surface, the alloying process between Cu alloy of the electrode and molten Zn of the sheet was reduced, due to the barrier action of the coatings, as well as the pitting (erosion) of the electrode was also remarkably reduced, and hence a slower growth rate of the tip diameter was obtained, as an indicator of the electrode life [20]. Post depositing treatment with laser of TiCP/Ni coating eliminated cracks and improved coating quality.

6. Conclusions

- Cold metal transfer (CMT) welding can be applied for overlaying with low dilution.
- Ceramic coatings with improved cavitation and wear resistance are obtained by plasma thermal spraying, followed by remelting with laser or electron beams.
- The structure of the deposited ceramic micro- layers has solid solutions with free oxides, with high micro-hardness of 772 HV1.
- In the cavitation erosion test, the degradation of the overlay is due to the combined effect of four factors: sensitivity to cold hardening, propagation of micro-cracks, pulling-out of some compounds; cohesionless of secondary brittle phases.

- The ceramic micro-layers have good wear resistance and adherence to the substrate.

- The laser treatment causes melting and solidifying of the electro-spark depositions (ESD); the refinement of structure and disappearance of micro-cracks were also noticed.

- The average friction force during the tribologic tests for the WC-Co coatings was approximately 35% lower after the laser modification.

- The seizure force of the WC-Co coatings after laser treatment increased about 16%.

- Laser treatment caused a 21% decrease of the micro-hardness of the WC-Co ESD coatings.

- After laser treatment, the roughness of the ESD coatings almost doubled; laser smoothing by melting the coating micro-peaks must be applied.

- Laser treatment caused a 32% increase in the adhesion of the electro-spark WC-Co coatings.

- Laser treatment caused an 8% decrease in the micro-hardness of the WC-Co-Al_2O_3 coatings.

- The favorable changes in the properties of electro-spark coatings after laser treatment lead to the improvement of the abrasive wear resistance.

- The overlaying processes are applied for coatings of the tightening parts of industrial and power systems, that operate at high pressure and temperature, such as valves, fittings, feeders, as well as on various tools.

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