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INVESTIGATION OF PHYSICAL FEATURES AND TECHNOLOGICAL CAPABILITIES OF CONTINUOUS OPTICAL DISCHARGE

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In order to study physical features and technological capabilities of continuous optical discharge, a number of laboratory stands and plasmatrons were developed, which were used to determine the ranges of variation of energy, gas-dynamic, chemical and design parameters, providing stability of processing operations. It was found that at the change of power of CO_2-laser radiation in the range of 1.5–6.0 kW, power of continuous optical discharge changes linearly, while power of laser radiation, passing through the discharge, can be regulated from 8 to 40 % of CO_2-laser radiation power. Shown is the possibility of additional energy input into continuous optical discharge from direct current source. Here, power of additional input can exceed that of laser radiation. It is rational to apply continuous optical discharge, together with laser radiation which passed through it, to produce new materials, nanostructured carbide and diamond films, spheroidizing of refractory materials, surface modification, surfacing and other related technologies. 14 Ref., 1 Table, 3 Figures.

Keywords: *continuous optical discharge, CO_2-laser radiation, surfacing, heat treatment, experiments, modes, metallography, structure, residual stresses*

In 1970 continuous optical discharge (COD) in gas was for the first time obtained experimentally and studied by Yu.P. Raiser [1]. In the first experiments, optical discharge plasma was freely located inside a stationary gas volume in the focal region of continuous CO_2-laser radiation. In 1978 there was the first report about development of a plasmatron [2], in which optical discharge stabilization in focused laser radiation is achieved by gas flow longitudinal in the direction of radiation. Possibility of free transfer of laser radiation energy to considerable distance, its concentration in small volumes by optical means, high temperature and degree of ionization in optical discharges open up the prospects for many practical applications. Until recently, however, work on this problem was focused on investigations of COD plasma proper in gases, and just the possibility of application of laser plasmatron in thermal and plasmochemical processes was noted [3–5].

Prospects for COD application were determined by its features and unique characteristics.

First, COD plasma can be generated in the majority of gas mixtures at atmospheric and higher pressure, while known «pure» technologies, based on application of plasma of high and superhigh purity (HF, SHF), are preferably applied at lower (below 100 Torr) pressures of gas mixtures, i.e. in vacuum chambers. At the same time, solution of many applied problems is essentially simplified, or even becomes possible only at development of technologies of plasmochemical synthesis and coating deposition directly under atmospheric conditions. Application of COD plasma, which can exist at atmospheric pressure, in combination with manipulators, opens up the possibility of coating deposition both locally, and on products of practically unlimited dimensions.

Secondly, high pressure of gases, i.e. considerable density of active molecules, in combination with record specific density of laser energy evolution in gas and high plasma temperature (15–20 thou K), create conditions for high-velocity synthesis of materials.

Thirdly, maintaining stable COD plasma does not require any structural elements for energy supply (electrodes, waveguides, resonators, etc.). There are no erosion products that usually contaminate the growing film in the traditional methods of plasmochemical deposition that allows producing chemically pure materials.

Wide acceptance of up to 2–10 kW laser units in industry and in research organizations stimulated performance of research and appearance of publications in this field [6–14].

The objective of this work is determination of COD physical parameters and technological capabili-

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ties of its application, as well as development of plasmatrons with plasma jet and laser radiation directed downward on the item. Design allowed for published data and results of our own experiments.

Experiments were conducted on different plasmatron models to determine optimum conditions of COD excitation and stable existence at different variations of laser radiation power, gas kind and flow rate, geometrical dimensions of the discharge, point of application of powder and gas precursors to the discharge, etc.

Energy parameters of the discharge were provided by CO_2-laser of TRIAGON 12000 model (ROFIN-SINAR Company, Germany). Technological stand was at 7.5 m distance from laser output window. Reflecting copper mirrors were used to transmit laser radiation by air to the process head, where it was focused by salt KCl lens with focal distance $F = 330$ mm. Head conical part ended in a nozzle 27 mm long with 12 mm inner diameter. During experiments the lens focal plane was located at 10 mm distance from nozzle edge, to which plasmatrons of various designs were abutted, by inserting the plasmatron into the nozzle to the depth of 20 mm. COD excitation was performed by short-time insertion of aluminium plate into laser radiation focal zone.

The Table gives the results of experiments on COD ignition and determination of the conditions of its stable existence in commercial argon jet, at variation of laser radiation power level on focusing lens (P, kW) and gas flow velocity in output nozzle of 12 mm diameter (Q, m/s). At power exceeding 1.5 kW, and argon flow velocity of more than 1.0 m/s, COD is excited and runs in a stable manner. Range of gas flow velocities, more suitable for technological operations, was selected for investigations (1–40 m/s).

It is known [10] that at subsonic velocities of gas flow of 0.1–0.6 m/s of atmospheric pressure and 1.2–6.0 kW power of CO_2-laser radiation, COD behaves as a solid and the gas flow moving over it, is heated at the discharge periphery and flows around it. COD high-temperature core is localized in the region of laser beam focus, rises along the beam for up to 10 mm distance and is elongated along the gas flow. Gas discharge temperature gradient decreases with increase of gas flow velocity. Retardation of the flow is observed on COD front, where the higher pressure zone is located and gas flowing around the discharge high-temperature region is realized [10].

Figure 1, *a*, *c* shows photos of COD under atmospheric conditions. COD stationary existence envisages equality of CO_2-laser radiation energy dissipated in gas and its dissipation due to thermal radiation emission, heat conductivity and heat removal by convective gas flow. Dependence of the coefficient of laser radiation absorption on temperature has a maximum in the region of 17–18 thou K at 1 atm in air, and threshold power is in the range of 1.8–2.0 kW, respectively. In argon at 1 atm threshold power is about 800 kW, and possible minimum temperature of plasma near the caustic is 12700 K [10].

Minimum threshold power of COD stable running decreases in the case of application of gas with a low ionization potential, poor heat conductivity and pressure increase. Figure 2 [14] shows experimentally measured isotherms of spatial distribution of plasma temperature of COD excited in air at atmospheric pressure, excited by CO_2-laser of 6 kW power [14]. Beam is directed horizontally from right to left. A certain asymmetry of isotherms is attributable to air flow generated by Archimedean force.

If laser beam of 1.5 to 2.0 kW power and argon flow with velocity of 0.59 m/s are directed vertically downwards, COD takes the shape of a sphere of about 15 mm diameter, and rises by approximately 1 cm in-

Values of process parameters, providing COD stable excitation and existence

P \ Q	0.147	0.294	0.442	0.589	0.884	1.179	1.47	2.21	2.047	3.684	4.42
1.0	–		–	–		–	–	–	–	–	–
1.5	–		+ –	+ –	+	+	+	+	+	+	+
2.0	+			+ –	+	+	+	+	+	+	+
2.5				+ –	+	+	+	+	+	+	+
3.0				+ –	+	+	+	+	+	+	+
3.5				+ –	+	+	+	+	+	+	+
4.0				+ –	+	+	+	+	+	+	+
4.5				+ –	+	+	+	+	+	+	+
5.0				+ –	+	+	+	+	+	+	+
5.5				+ –	+	+	+	+	+	+	+
6.0				+ –	+	+	+	+	+	+	+

Note. + — stable COD; – — unstable.

Figure 1. Laboratory stands for investigation of COD technological capabilities: *a* — COD, running in an argon jet, in atmosphere; *b* — hybrid interaction of COD and microplasma; *c* — plasmatron operating on COD base in nitrogen; *d* — treatment of bodies of revolution with COD; *e* — hybrid plasmatron with COD pumping by DC arc; *f* — COD surfacing

versely to the direction of laser radiation propagation; at flow velocity of 1.0 m/s COD core is a bright luminous ellipse of 7×17 mm size, which moves down for 7–8 mm, and at the velocity of 4.42 m/s COD moves down for 15 mm and has the form of a bright white ellipse, the central part of which is of 8×22 mm size (Figure 1, *a*).

COD placing inside the plasmatron increases its stability, which depends, at other conditions being equal, on inner diameter of plasmatron channel. In plasmatron with inner diameter of 48 mm at beam power of 2.0 kW the discharge is stable at flow velocities of 0.14–3.0 m/s. In a plasmatron of 22 mm inner diameter and 115 mm length, at 2.0 kW power of laser radiation the discharge is stable at flow velocity in the range of 0.1–10.0 m/s. At atmospheric pressure and argon flow velocity of 1.0 m/s, it was not possible to set the upper power limit. In an optical plasmatron, the temperature of the discharge central part is by 1–3 thou K higher, than COD temperature in stationary gas.

To enhance COD technological capabilities, at limited power of laser source, experiments were conducted to increase COD power by passing current through the discharge without inserting additional electrodes. Under the conditions of this experiment, COD does not touch plasmatron walls, and the jet

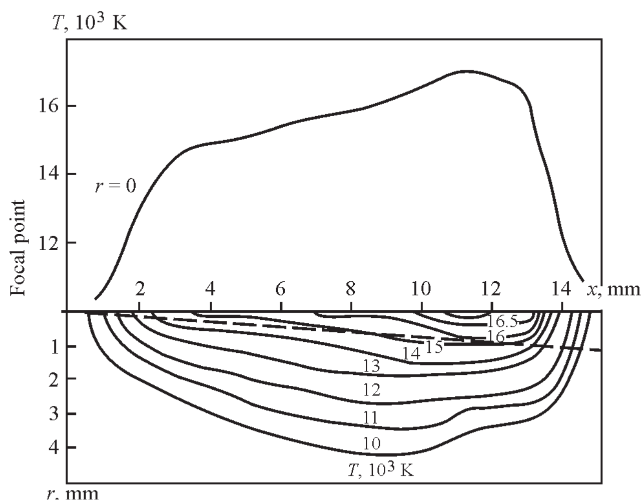

Figure 2. Isotherms of spatial temperature distribution of COD (*bottom*) and temperature distribution on beam axis (*on top*)

formed by plasma discharge, touches the item. Diameter of plasmaforming nozzle was 3 mm, the gap between the nozzle and item was 8 mm. Positive potential of welding source was connected to plasmatron case, and negative potential — to the item. Current of additional discharge was 40 A, voltage was 31 V. About 1240 W were released in the discharge. Current flows through the cold layer of gas, due to greater mobility of plasma electrons. At polarity change current does not flow. Figure 1, *e* shows COD additionally preheated by direct current.

Interesting results were obtained at COD intersecting argon plasma flow, generated by arc plasmatron (Figure 1, *b*). In this device, gaseous and powder precursors can be inserted both into COD plasma region, and into arc plasmatron plasma.

An important task in COD application is realization of laser-plasma technology of gas-phase synthesis of diamond films from multicomponent gas mixtures and deposition of these films on the surface of parts of machines and mechanisms, working surfaces of tools, etc [9]. COD generates dense equilibrium plasma with small temperature gradient in the cross-section of laminar gas flow — these are optimum conditions for decomposition of active components of gas mixtures and increasing the rate of diamond film deposition. Substrate temperature is very important for film deposition rate and its quality. Stabilization of its optimum temperature (about 800 K) was performed by different design and energy parameters of the device, namely adjustment of crossover position in the plasmatron; plasma-substrate distance; design of gas and contact coolers; variation of laser power and gas flow velocity. Fraction of laser radiation reaching the substrate can be reduced due to elongation of COD high-temperature component. This requires reducing plasmatron channel diameter and increasing gas flow velocity. Elongation of high-temperature jet in COD will enhance laser beam refraction and power density on the item will decrease. This will allow avoiding overheating of deposited film central part, if power distribution in the beam is a Gaussian one. Qualitative estimates of synthesized films and individual crystals, as well as the spectra of their combined scattering are not given in this paper.

COD unique properties open up broad technological capabilities in the field of welding and related technologies. A laboratory stand was developed for determination of the possibility of changing the dimensions of powder material particles (powder dispersion) under COD impact. The stand consists of plasmatron of MP-4 model and its power source MPU-4M, allowing operation at up to 45 A currents at up to 40 V voltage. According to technological schematic given in [12], plasmatron was placed so that microplasma jet passed through COD normal to laser radiation axis (Figure 1, *b*). Used were powders of 40–60 μm granulation with three types of meltability, namely $Al_2O_3 + TiO_2$ refractory powder (melting temperature of about 2200 °C), self-fluxing powder PG-12N-02 and PG-AN6 of N–Cr–B–Si system with medium values of meltability (melting temperature of 1000–1200 °C), as well as low-melting powder PG-19M-01 (melting temperature of 885–1020 °C).

During research performance splats were prepared to determine the degree of plasma discharge influence on powder particle. For this purpose powder particles which have flown through COD, shot-through by arc microplasma normal to laser beam axis, were deposited on object plates. Plates with a deposit were examined in optical microscope MBS-9. Investigations showed that refractory powders are poorly melted off by COD in view of the short time of staying in the discharge. Powders with low meltability values lend themselves too readily to COD impact and are prone to complete evaporation. Nickel-based self-fluxing powders with medium meltability values (melting temperature of 1000–1200 °C) proved to be the best. A tendency was established of refinement of power particles transported through COD by microplasma jet. Particle size was reduced to 30 μm in approximately 20–25 % of the total quantity of powder.

The next step in investigation of COD capabilities in the area of spheroidizing, crushing and refining of powders, was manufacturing a laser plasmatron based on COD (Figure 1, *c*). Investigation of technological capabilities of laser plasmatron with 3 mm nozzle diameter showed that the best conditions for its operation are in place at application of 2.0–3.0 kW radiation power of CO_2-laser and flow velocity of plasma gas (argon) of 5–10 l/min. About 1.5–2.5 kW was applied to optical plasma, and 20% of laser power passed through COD. Optical discharge length was in the range of 15–20 mm, i.e. for 7–10 mm up and down with respect to focus. Length of plasma jet, leaving the laser plasmatron, was equal to 5–10 mm, depending on gas flow velocity.

A laboratory stand was manufactured on the base of three-axis manipulator to perform experiments on steel sample surfacing by laser beam with simultaneous COD impact (Figure 1, *f*). It was used to spray samples with Ni–Cr–B–Si system powders from PG-

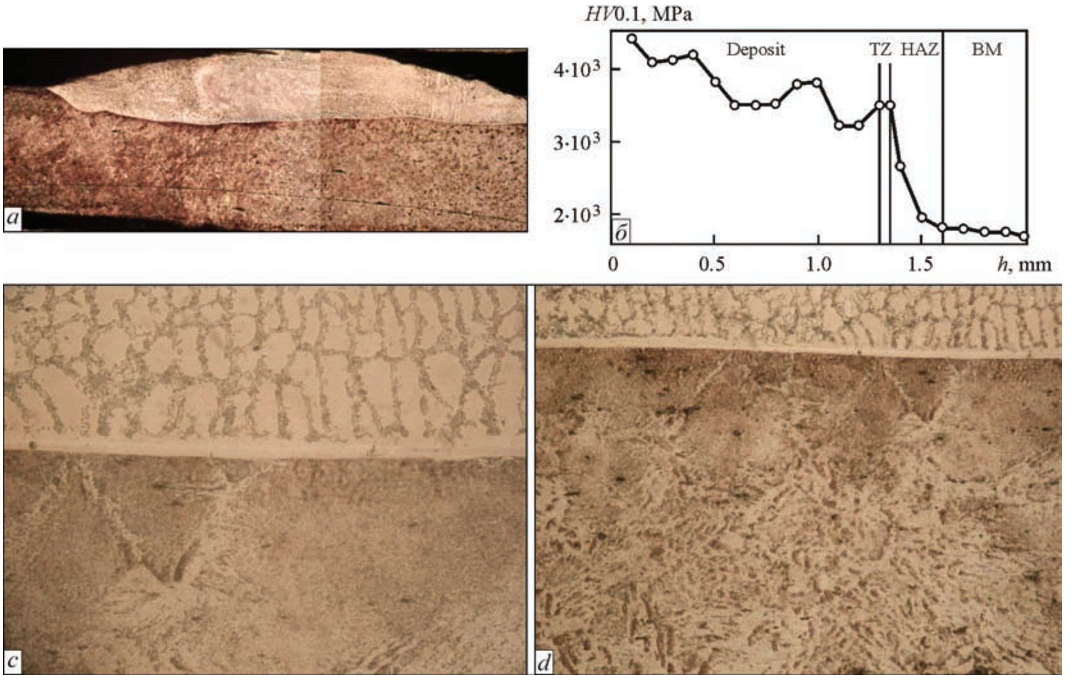

Figure 3. General view of deposited bead (*a*, x25) with distribution of microhardness *HV*0.1 by depth *h* of deposited layer (*b*), transition zone (*c*, ×400) and HAZ in base metal (*d*, ×200)

12N-02 (*HRC* 40–45) and PG-AN6 (*HRC* 60–65) alloys [13] by laser and hybrid laser-COD processes. Here, in all the cases laser radiation power was equal to P = 0.7 – 0.8 kW, COD power was P_{COD} = 2.0–2.2 kW, deposition rate was 40 m/h, and deposited bead width was 4 mm. Obtained samples were ground for further metallographic and radiographic investigations.

Hybrid laser-COD surfacing enabled produced defectfree layers with finely-dispersed cast structure, consisting of austenite matrix and δ-ferrite, which precipitated along the boundaries of crystallites and cells (Figure 3, *a*). Quantity of δ-ferrite was 15–25 % (measurements were performed in «Ferritegehalt-messer 1.053» instrument). Microhardness distribution was measured in the direction from deposited layer surface towards base metal (100 g load, 100 μm step). These measurements showed greater uniformity of microhardness distribution for laser-COD surfacing than for laser surfacing (Figure 3, *b*). Transition zone size was equal to about 10 μm (Figure 3, *c*), and heat-affected zone depth was up to 0.2 mm (Figure 3, *d*).

Thermal cycle modification in hybrid laser-COD surfacing promotes elimination of such characteristic defect of deposited layers as microcracks, as well as producing layers of sufficiently high hardness. Here, comparatively small dimensions of the HAZ (200–300 μm) and transition zone (10–15 μm) are indicative of successful energy input.

Analysis of the results of deposition of layers from PG-12N-02 and PG-AN6 alloys of Ni–Cr–B–Si system on steel of St3ps type, made by laser and laser-COD processes, revealed that cracking index decreased from 40–60 to 20–30 %, respectively. Stresses of the Ist kind, measured in deposited layers by X-Ray phase technique, using X-ray diffractometer DRON-2, were also decreased. For PG-12N-02 and PG-AN6 alloys, deposited by the laser process, they were equal to –200 and –510 MPa, respectively, whereas in layers, deposited by hybrid process, they were equal to +120 and –310 MPa, respectively. Change of sign from «–» to «+» is indicative of the change of compressive to tensile stresses.

Investigations of heat treatment of samples from stamped steel 20Kh13 were conducted with minimum surface flashing (to the depth of 0.1–0.3 mm) with CO_2-laser radiation. Here, laser quenching was performed in the following mode: P_{las} = 1.5 and 3.0 kW; v = 60 m/h; d_b = 4–5 mm; Q_{Ar} = 25–30 l/min; and hybrid laser-COD quenching — in the following mode: P_{las} = 1.5 KW; d_b = 4–5 mm; P_{pl} = 1.5 kW; d_{pl} = 8 mm; v = 60 m/h; Q_{Ar} = 25 – 30 l/min. Produced quenched paths were used to cut out templates of 10×10×5 mm size, in which internal stresses of the Ist kind were measured in these paths by the method of X-ray phase analysis. Measurements showed that stressed state of the layers strengthened by laser process, was equal to about 470 MPa. Application of laser-COD strengthening allows reducing this value to approximately 260 MPa.

The authors believe that additional advantages of COD application at synthesis of polycrystalline diamond films can be achieved by changing the shape of laser radiation intensity from Gaussian to rectangular one.

Conclusions

1. Investigations of the features of COD existence showed that COD power changes linearly in 1.5–6 kW range of powers of CO_2-laser radiation, which has passed through focusing lens, while laser radiation component, which has passed through COD, can be equal to 10–30 %, depending on plasmatron design and values of process mode parameters. This allows using COD simultaneously with laser radiation which has passed through it, in the field of surface treatment technologies.

2. Possibility of applying additional electric power to COD was established.

3. To conduct the processes of surfacing and heat treatment of surfaces, it is rational to combine COD with the action of unfocused laser radiation (up to 2–4 mm diameter). The best results were obtained at COD power of 1.5–2.5 kW and 0.7–1.5 kW power of laser radiation, which has reached the substrate.

4. COD influence on the results of laser surfacing and heat treatment of surfaces consists in lowering residual internal stresses by 40–60 % through thermal cycle modification.

1. Generalov, N.A., Zimakov, V.P., Kozlov, G.I. et al. (1971) Experimental investigation of continuously burning optical discharge. *ZhETF*, 61(**1**), 1434–1446.
2. Kozlov, G.I. (1978) Laser plasmatron with gas flow. *Pisma v ZhETF*, 10(**4**), 586–589.
3. Raizer, Yu.P. (1980) Optical discharges. *UFN*, 132(**3**), 549–581.
4. Zimakov, V.P., Kuznetsov, V.A., Kedrov, A.Yu. et al. (2009) Gas laser for efficient maintenance of plasma of continuous optical discharge in scientific and technological applications. *Kvantovaya Elektronika*, 39(**9**), 797–801.
5. Bolshakov, A.P., Kono, V.I., Vostrikov, V.G. et al. (2008) Examination of plasma optical discharge in multicomponent mixtures of molecular gases. *Ibid.*, 38(**2**), 165–168.
6. Zimakov, V.P., Kuznetsov, V.A., Kedrov, A.Yu. et al. (2009) Refraction of laser radiation in plasma of continuous optical discharge in gas flow at atmospheric pressure. *Optika Atmosfery i Okeana*, 22(**11**), 1023–1028.
7. Franzen, D.L. (1973) Continuous laser-sustained plasmas. *J. Appl. Phys.*, 44, **4**, 1727–1732.
8. Kozlov, G.I., Kuznetsov, V.A., Masyukov, V.A. (1979) Continuous optical discharge in molecular gases. *ZhTF*, 49(**11**), 2304–2310.
9. Bolshakov, A.P. (2007) *Synthesis of polycrystalline diamond films using laser plasmatron*: Syn. of Thesis for Cand. of Phys.-Mat. Sci. Moscow: RGB.
10. Raizer, Yu.P. (1996) Continuous optical discharge — maintenance and generation of dense low-temperature plasma by laser radiation. *SOZh*, **3**, 87–94.
11. Kolumbaev, E.B., Lelevkin, V.M. (2002) Numerical analysis of characteristics of optical discharge in air. *Vestnik KRSU*, 2(**2**), 76–83.
12. Shelyagin, V.D., Krivtsun, I.V., Borisov, Yu.S. et al. (2005) Laser-arc and laser-plasma of welding and coating technologies. *The Paton Welding J.*, **8**, 44–49.
13. Borisov, Yu.S., Khaskin, V.Yu., Vojnarovich, S.G. et al. (2012) Combined laser-microplasma cladding with powders of Ni–Cr–B–Si system alloys. *Ibid.*, **11**, 16–22.
14. (1992) *Physical encyclopedia*. Moscow: Great Russian Encyclopedia.

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