Controlled processes at laser coating deposition

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Abstract. A description of the method is given of coating deposition under irradiation with a horizontal laser beam of a gas-dust medium which is an ensemble of micro-particles moving in the gas in the form of a free vertical jet. A number of coatings are obtained on various substrates and the results of measurements of their characteristics are presented. A setup based on a cw CO\textsubscript{2}-laser for the synthesis of diamond coatings in optical discharge plasma in the laser plasmatron mode has been created. The effect of spherical lens aberrations on the discharge maintenance thresholds is established. A diamond film was obtained on the surface of a tungsten substrate when a plasma jet was expelled into atmospheric air. An automatic system for measuring surface temperature in real time has been developed and created. The system was tested for laser cladding of metal powder in a pilot production.

1. Introduction
To increase the service life of machine parts and mechanisms, processing tools functional coatings with the necessary properties are applied to their surface [1]. Products obtained by the deposition of semiconductor materials are used in electronic and optoelectronic devices [2]. The use of lasers for these purposes is of particular interest. This is due to the relative simplicity of the laser method and the possibility of evaporation of almost any material in the PVD method of deposition, and with the possibility of increasing the working pressure in the gas-discharge plasma if the CVD method of deposition used is based on the use of optical discharge plasma.

This work presents the results of studies of the method of coating deposition during laser irradiation of a gas-dust medium in the form of a free vertical jet of micro-particles in a gas [3,4], and the main parameters of a laser plasmatron for applying diamond coatings [5]. It is also reported about the creation of a surface temperature monitoring system in real time and the results of its tests.

2. Coating by laser irradiation of a gas-dust medium

2.1. Experimental setup
Two deposition schemes were used schematically shown in figure 1. The horizontal laser beam \( I \) is focused on the axis of the gas-dust medium \( 2 \), which is an ensemble of micro-particles moving in the
gas at a controlled pressure and composition in the form of a free vertical jet. The formation of the jet and the change in the flow rate of particles in the jet is carried out using a mechanical dispenser. The source of laser radiation is a Yb fiber laser or a CO\textsubscript{2}-laser. The laser operates in a pulsed or repetitively pulsed mode. The caustic length of the laser beam exceeds the diameter of the jet, therefore, the average radiation intensity \( I_0 \) along the diameter is practically constant and for a fiber laser is \( 7 \times 10^5 \text{ W/cm}^2 \), and for a CO\textsubscript{2}-laser it does not exceed \( 3.5 \times 10^4 \text{ W/cm}^2 \). The products of interaction of radiation with particles are deposited on the substrate and form a coating. Deposition takes place in a chamber at a controlled gas pressure. To heat the substrate, laser radiation 6 (figure 1, a) or an ohmic heater (figure 1, b) is used. Electrode 5 is used to study the effect of a constant electric field or a direct current glow discharge on the deposition.

![Figure 1. Application schemes.](image)

2.2. Characteristics of the gas-dust medium

2.2.1. Particle temperature. To measure the temperature of particles interacting with laser radiation, we used a small-sized spectrometer calibrated to the radiation of a standard lamp in the wavelength range of 450 - 800 nm. The choice of smooth regions in the emission spectra, free of atomic lines and molecular bands, makes it possible to find the temperature \( T \) of particles for two arbitrary values of the wavelengths \( \lambda_1 \) and \( \lambda_2 \) using the relation \( T = \frac{hc}{k} \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \left( \frac{1}{\ln \frac{b(\lambda_1,T)e(\lambda_1,T)}{b(\lambda_2,T)e(\lambda_2,T)}} + 5 \ln \frac{\lambda_1}{\lambda_2} \right) \) (1),

where \( h \) is Planck's constant, \( c \) is the speed of light, \( k \) is Boltzmann's constant, \( e(\lambda_1,T) \) and \( e(\lambda_2,T) \) are emissivity factors, \( b(\lambda_1,T) \) and \( b(\lambda_2,T) \) are spectral brightness proportional to the radiation intensity in the spectrum. Assuming that for close values of \( \lambda_1 \) and \( \lambda_2 \), the emissivity factors are the same, they can be excluded from (1) and the temperature can be determined from the measured ratio of the corresponding radiation intensities. The results of determining the temperature using this technique show that when AlN particles with an average radius of 25 \( \mu \text{m} \) are irradiated with fiber laser radiation at \( I_0 = 7 \times 10^5 \text{ W/cm}^2 \), the temperature is \( T = (2470 \pm 370) \text{ K} \), and its maximum value 2840 K exceeds the evaporation temperature of AlN (2790 K).

It is of interest to estimate the threshold radiation intensity for particle evaporation and compare it with the value of \( I_0 \).

2.2.2. The threshold radiation intensity for particle evaporation. To estimate the threshold radiation intensity \( I_v \) required for evaporation, we used the following particle energy balance equation

\[ T = \frac{hc}{k} \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \frac{1}{\ln \frac{b(\lambda_1,T)e(\lambda_1,T)}{b(\lambda_2,T)e(\lambda_2,T)}} + 5 \ln \frac{\lambda_1}{\lambda_2}, \]
\[ ASI \cdot \delta t = m(Q_m + Q_v + cT_v) + \delta t (aAST_v^4 + a_TST_v), \]  

(2)

where \( A \) is the absorption capacity of the material, \( S \) is the surface area of the particle, \( T_v \) is the evaporation temperature, \( c \) is the specific heat capacity, \( Q_m \) is the specific melting energy, \( Q_v \) is the specific evaporation energy, \( \sigma \) is the Stefan-Boltzmann constant, \( a_T \) is the heat transfer coefficient for laminar flow around spherical bodies [7], \( \delta t = 2w/v \) is the time of flight of the particle through the caustic region of radius \( w \), \( v \) is the speed of flight. The velocity depends on the distance \( h \) between the outlet of the dispenser and the axis of the laser beam and to calculate it the equation \( dv/dt = g - 6\pi \eta rv/m \) was solved under the initial condition \( v = 0 \), where \( g \) is the gravitational acceleration, \( \eta \) is the dynamic viscosity of the gas, \( r \) and \( m \) is the radius and mass of the particle, respectively. This model does not take into account the change in \( m \) and \( \delta t \) during particle evaporation and gives an upper estimate for the value of \( I_r \).

The results of calculations using expression (2) for AlN particles with \( r = 25 \mu m \) at a nitrogen pressure \( p_{N_2} = 750 \) Torr for fiber laser radiation \( (A = 0.3, w = 0.23 \) mm) show that \( I_r \approx 6 \cdot 10^4 \) W/cm\(^2\) < \( I_0 = 7 \cdot 10^5 \) W/cm\(^2\) with the same \( h = 3.5 \) cm in calculations and experiments. Therefore, one can expect the evaporation of these particles, which corresponds to temperature measurements. Note that the calculations of \( I_r \) for other pressures will differ little due to the weak dependence of \( \eta \) on \( p \) [8].

The evaporation of particles at relatively low values of the radiation intensity sets the problem of determining the possibility of optical breakdown in vapors.

### 2.2.3. On the possibility of optical breakdown of a gas-dust medium.

Let us use the following expressions for the threshold absorption coefficient of laser radiation \( a_{th} \) and the time of gas transition to a high-temperature state \( \tau_r \) obtained in [9] for the thermal explosion model

\[ a_{th} = \frac{\lambda_1 T_1}{I_0^2 (1 + R) \alpha}, \]

(3)

\[ \tau_r \approx \frac{c_i \rho_1 T_1}{(1 + R) I a_{th}}, \]

(4)

where \( T_1 \) is the temperature of the vapor, \( \lambda_1 \) is the thermal conductivity of the vapor, \( c_1, \rho_1 \) are the specific heat and density of the vapor, respectively, \( r_0 \) is the size that determines the heat removal, \( R = 1 - A \) is the radiation reflection coefficient, \( \alpha = d \ln \alpha / d \ln T \).

For the breakdown of a gas-dust medium, two conditions must be satisfied: first, the interaction time of radiation with particles \( \delta t = 2w/v \) must be greater than \( \tau_r \) and, second, the absorption coefficient of radiation \( \alpha \) must exceed \( a_{th} \). The absorption coefficient \( \alpha \) exponentially increases with decreasing ionization potential \( I_i \), therefore, the fulfillment of the second condition becomes more probable when particles with a low ionization potential are ionized. Such particles can be, for example, Al atoms \( (I_i = 5.98 \) eV\), which appear in the interaction region due to the dissociation of AlN at the evaporation temperature.

Calculations according to expressions (3), (4) for Al vapor at \( T_1 = 3000 \) K and atmospheric pressure \( (\lambda_1 \approx 10^{-3} \) W/(cm-K), \( c_1 = 0.78 \) J/(g-K), \( \rho_1 = 1.2 \cdot 10^{-4} \) g/cm\(^3\)) with considering \( A = 0.3 \) and \( \alpha = 10 \), for \( r = r_0 = 10 \) \( \mu m \) and 100 \( \mu m \), for a fiber laser \( (I = I_0 = 7 \cdot 10^5 \) W/cm\(^2\)) respectively, give \( a_{th} = 0.25 \) cm\(^1\), \( \tau_r = 9.4 \cdot 10^{-7} \) s and \( a_{th} = 0.003 \) cm\(^1\), \( \tau_r = 9.4 \cdot 10^{-5} \) s, and for a CO\(_2\) laser \( (I = I_0 = 3.5 \cdot 10^4 \) W/cm\(^2\)), respectively: \( a_{th} = 5.04 \) cm\(^1\), \( \tau_r = 9.4 \cdot 10^{-7} \) s and \( a_{th} = 0.05 \) cm\(^1\), \( \tau_r = 9.4 \cdot 10^{-5} \) s.

At the same time, the calculation by formulas [10] of the absorption coefficient of radiation in a thermal plasma of Al vapor at atmospheric pressure and \( T_1 = 3000 \) K shows that for a fiber laser \( \alpha \approx 10^{-7} \) cm\(^1\), and for a CO\(_2\)-laser \( \alpha \approx 10^{-5} \) cm\(^1\).

Thus, for particles with an order of magnitude different in size, for the radiation of both lasers the inequality \( \alpha \ll a_{th} \) is fulfilled and breakdown due to violation of the second condition becomes
impossible, although the first condition ($\delta t = 20 \text{ ms} \gg \tau_{tr} = 9.4 \cdot 10^{-7} \text{ s}$ for $r_0 = 10 \mu\text{m}$ and $\delta t = 1 \text{ ms} \gg \tau_{tr} = 9.4 \cdot 10^{-5} \text{ s}$ for $r_0 = 100 \mu\text{m}$) is satisfied with a margin.

2.3. Coating a metal substrate

The application scheme shown in figure 1,a was used. The radiation source is a repetitively pulsed fiber laser with a pulse duration of $\tau_p = 50 \text{ ms}$. Substrate 4 and electrode 5 are plates of steel St.3 with a diameter of 20 mm and a thickness of 1.5 mm with a central hole for the transmission of laser beam.

2.3.1. AlN coatings. Figure 2 shows photographs of coatings on etched substrates 4 obtained by irradiating AlN particles at $p_{N_2} = 1.8 \text{ Torr}$ and a pulse repetition rate $f = 0.5 \text{ Hz}$. The substrate in figures 2,a and 2,b was, respectively, an anode and a cathode (discharge current $I_d = 10 \text{ mA}$, discharge voltage $U_d = 280 \text{ V}$, $d = 20 \text{ mm}$, $d_1 = 10 \text{ mm}$). The deposition was carried out for a time $t = 60 \text{ s}$ at a substrate temperature $T_s = 370^\circ\text{C}$ (figure 2,a) and $T_s = 405^\circ\text{C}$ (figure 2,b).

The X-ray diffraction spectra of the coatings showed the presence of only groups of lines AlN, $\alpha$-Fe and Fe$_2$O$_3$. The last two groups relate to the substrate base.

The coating on the anode substrate is characterized by strong adhesion. This may be due to the charging of dust particles in the discharge plasma by plasma electrons [11] and their acquisition of an additional velocity $v_u$ when moving in an accelerating potential $U$ towards the substrate

$$v_u \approx 0.9 (qU/\rho r^3)^{1/2}, \quad (5)$$

where $q$ is the particle charge in units of elementary charge, potential $U$ is expressed in V, density $\rho$ in g/cm$^3$, radius $r$ in $\mu\text{m}$ and $v_u$ in cm/s. According to [12], an increase in the velocity of particles during deposition on a substrate improves the adhesion of the coating to the substrate. Let's make a numerical estimate. Since a discharge with a current $I_d = 10 \text{ mA}$ is a normal glow discharge, the value $p_{N_2} d_c = 0.42 \text{ Torr} \cdot \text{cm}$ [10]. Therefore, the thickness of the cathode layer is $d_c = 0.23 \text{ cm}$, and the voltage $U = U_d - U_c = 65 \text{ V}$ is applied to the positive column of length $d_pc = d - d_c = 1.77 \text{ cm}$, where $U_c = 215 \text{ V}$ is the cathode drop. Substituting this value of $U$ into formula (5), for AlN particles of radius $r = 1 \mu\text{m}$ and 5 $\mu\text{m}$, taking into account $q \sim 10^5$ and $\rho = 3.26$ g/cm$^3$, we have, respectively, $v_u = 1300 \text{ cm/s}$ and 115 cm/s.

![Figure 2. Photographs of AlN coatings on etched substrates of steel St.3 for the anode (a) and cathode (b) substrate.](image)

2.3.2. Ti coatings. The Ti coating obtained by irradiating Ti particles under conditions similar to those for AlN particles also has excellent adhesion to the etched anode substrate 4.

The X-ray diffraction spectra contain only the $\alpha$-Ti lines and related to the base the $\alpha$-Fe lines. The TiN compound is not formed, apparently, because of the high (3280°C) temperature of evaporation of Ti and insufficient radiation intensity for evaporation. The coating is a solidified titanium droplet. It can be considered as the Ti surfacing on steel St.3 obtained under our conditions.

Similar experiments were carried out with a substrate pretreated with a jet of quartz sand. The deterioration in adhesion of the coating can be attributed to the presence of a sublayer of sand particles. This is evidenced by the X-ray diffraction spectra containing not only the $\alpha$-Ti and $\alpha$-Fe lines, but also the $\alpha$-SiO$_2$ lines.
2.4. Deposition of films on a dielectric substrate

The scheme in figure 1,b was used with a quasi-cw CO₂ laser [13] with an adjustable pulse duration \( t_p \) = 10 - 100 ms and a constant output power during the pulse varying within the range \( P = 0.4 \) - 1.1 kW. With a focusing radius \( w = 0.94 \) mm, the average value of \( I_0 \) after attenuation the power on the auxiliary optical elements is given by the expression \( I_0 = 3.13 \times 10^4 \) \( P [kW] \). The substrates are glass plates based on \( \text{Al}_2\text{O}_3 \) or crystalline silicon 1 mm and 0.4 mm thick, respectively, heated to a temperature \( T_s \approx 350 \)°C. The deposition was carried out at varied values of \( P \), \( t_p \), the number of pulses \( N \) and the pressure \( p \) of the gas at a constant \( h = 2.5 \) cm and a fixed distance of 1 cm of the horizontal substrate from the axis of the laser beam.

2.4.1. CdS films. To form a jet of micro-particles, CdS powder with a particle size of \( 2r = 10 \) - 50 \( \mu \)m was used. Ar serves as a buffer gas.

It was shown that the thickness of the resulting films is proportional to \( P \), \( t_p \) or \( N \) for fixed other parameters. For example, at \( P = 1.05 \) kW \( (I_0 = 3.3 \times 10^4 \) W/cm\(^2\)) \( , \) \( t_p = 50 \) ms, \( N = 3 \) and \( p_{Ar} = 30 \) Torr, the thickness found with the shear interferometer is \( d_r = 70 \) nm, which leads to the velocity deposition \( v_0 = d_0/(Nt_p) = 28 \) \( \mu \)m/min.

The calculation by expression (2) of the threshold intensity \( I_0 \) for CdS particles of the indicated size at \( w = 0.94 \) mm and \( h = 2.5 \) cm gives \( I_0 << I_0 \). Due to the effective dissociation of CdS upon evaporation, the formation of a CdS film on the substrate is likely due to the association of Cd and S atoms near the substrate or on its surface. In this case the crystal structure of the film corresponds to the structure of the initial material. We were convinced of this by measuring the X-ray diffraction spectrum of the film on a glass substrate, and also comparing its luminescence spectrum with the luminescence spectrum of a CdS single crystal.

2.4.2. AlN films. The deposition was carried out in an argon or nitrogen atmosphere. Silicon substrates were used. The spread of the particle size in the powder is \( 2r = 10 \) - 50 \( \mu \)m. The composition of the initial powder is close to stoichiometric with an atomic concentration of \([\text{Al}] = 49.86\% \) and \([\text{N}] = 50.14\% \). The maximum of the luminescence spectrum of the powder falls at a wavelength of 360 nm and is shifted by 140 nm relative to the maximum of the luminescence spectrum of the AlN single crystal (220 nm). Note that due to an increase in \( w \) and, consequently, \( \delta t \), the threshold evaporation intensity \( I_0 \) of AlN particles for the conditions of these experiments will be less than the threshold intensity in experiments with a fiber laser, and even for particles with \( 2r = 50 \) \( \mu \)m satisfies the condition \( I_0 = 6 \times 10^4 \) W/cm\(^2\) \(< I_0^{\text{max}} \), where \( I_0^{\text{max}} = 3.4 \times 10^4 \) W/cm\(^2\) \( \) at \( P = 1.1 \) kW.

When the deposition occurs in an argon atmosphere, the X-ray diffraction spectra of the film contain both AlN and Al lines. The appearance of Al can be explained by the dissociation of AlN and the subsequent condensation of aluminum vapor. As a result, microscopic formations of pure aluminum may be present on the surface in the form of solidified drops. The consequence of this is the violation of the stoichiometry of the film: the \([\text{Al}]\)\([\text{N}]\) ratio for different parts of the surface that do not contain Al drops is in the range 0.9 - 0.94.

During deposition in nitrogen, the deviation of the AlN composition from stoichiometric towards an increase in nitrogen concentration occurs, as compared to deposition in argon. Qualitatively, this effect can be explained by the partial dissociation of molecular nitrogen during its interaction with the surface of particles heated in the field of laser radiation. On the other hand, the resulting excess of atomic nitrogen shifts the equilibrium of the dissociation reaction of the AlN molecule to the left, which prevents the condensation of aluminum vapor and, in fact, means the possibility of AlN synthesis under our conditions.

To study this possibility, we used particles of chemically pure aluminum with \( r = 10 \) \( \mu \)m and a nearly spherical shape, moving in nitrogen. The calculated value of \( I_0 \) is equal to \( I_0 = 10^4 \) W/cm\(^2\) \(< I_0^{\text{max}} = 3.4 \times 10^4 \) W/cm\(^2\), so that the evaporation of particles is possible. The concentration curves measured are indicative of the existence of AlN material on the surface.
3. Laser plasmatron for diamond coating deposition

A continuous optical discharge in the laser plasmatron mode is an effective means of diamond coatings synthesizing. The absence of a vacuum chamber and electrodes allows to synthesize in atmospheric air in sterile plasma, and the possibility of operating a plasma-chemical reactor at atmospheric (and above atmospheric) pressure leads to an increase in the growth rate of coatings. The capabilities of this method were demonstrated in [14] and were further developed in [15], when using reagent gases CH$_4$ and H$_2$ in a mixture with a plasma-forming gas Xe or Ar, coatings with an area of ~ 1 cm$^2$ were obtained on tungsten and molybdenum substrates at a rate deposition 30-50 μm/h.

This section reports on the creation of a setup with a laser plasmatron based on a modern cw CO$_2$-laser and presents the results of experimental studies.

3.1. Experimental setup

3.1.1. Setup diagram. The setup diagram is shown in figure 3. The laser beam 5 emerging from the laser generating unit 1 is fed to its telescoping system 6 and, after reflecting from the mirror 7, enters into the plasmatron 8. The setup is equipped with a cooling system 3, its operation is controlled by a control unit 2 connected to a personal computer.

![Figure 3. Setup diagram.](image)

The output radiation power $P$ of the laser reaches 3.5 kW, the radiation wavelength $\lambda = 10.6$ μm. With a beam radius at the output $r = 10$ mm and a quality index $M^2 = 1.05$, the divergence of the output radiation is $\gamma = M^2 \lambda/(\pi r) = 3.5 \times 10^{-4}$ rad. The use of replaceable nozzle blocks allows us to ejection the plasma jet both vertically downward and in the horizontal direction due to additional lateral blowing of the working gas beyond the edge of the nozzle. The working gas is Ar or a mixture of Ar:H$_2$:CH$_4$ = 1.0.07:0.0021 gases at atmospheric pressure.

3.1.2. Radiation focusing. The focusing lens of the plasmatron is installed at the entrance hole of radius $r_p = 23$ mm. At $r = 10$ mm, the ratio $r/r_p \approx 0.43$, which leads to an irregular heat load on the lens. For a more uniform filling of the lens aperture with radiation, the output beam was expanded by a telescoping system 6.

The radius of the focal spot of the plasmatron lens, taking into account its spherical aberrations, has the form

$$r_f = \frac{a(2r_0)^3}{f^2} + \gamma_0 f,$$

where $f$ is the focal length of the lens, $a = 0.044$ is the lens parameter, $r_0 = rH$ and $\gamma_0 = \gamma/H$ are the beam radius and radiation divergence after telescoping, $H$ is the magnification of the telescope.
In the experiments the $H$ value is equal to $H = 2.06 \ (r_0/r_p \approx 0.9)$, and lenses with $f = 152 \ \text{mm}$ and 170 mm were used. Comparison for these lenses of the $r_f$ values and the caustic length $z_k = kr_f/\gamma^2$ (here $k = 2\pi/\lambda$, $r_0 = \gamma r_f$), respectively, gives: $r_f = 0.151 \ \text{mm}$, $z_k = 2.23 \ \text{mm}$ and $r_f = 0.127 \ \text{mm}$, $z_k = 2.13 \ \text{mm}$. It can be seen that the $z_k$ values are close to each other (with an accuracy of 5%), and the radii $r_f$ differ noticeably (by about 20%). These features should influence on the discharge maintenance thresholds.

3.2. Discharge maintenance thresholds in gas flow

Figure 4 shows the results of measurements of the threshold power $P_{th}$ for maintaining the discharge in Ar versus the gas flow rate $Q$ for $f = 152 \ \text{mm}$ and 170 mm with a vertical jet extraction. The gas velocity $v_0$ is related to the flow rate $Q$ by the relation $v_0[\text{cm/s}] = 33.3Q[\text{l/min}]$. A similar dependence for Ar for $f = 170 \ \text{mm}$ with horizontal extraction is shown in figure 5 ($v_0[\text{cm/s}] = 43.5Q[\text{l/min}]$).

![Figure 4](image1.png) ![Figure 5](image2.png)

Figure 4. Dependences of $P_{th}$ on $Q$ for Ar with vertical jet extraction. $f = 170 \ (1)$ and 152 mm (2).

Figure 5. Dependence of $P_{th}$ on $Q$ for Ar with horizontal jet extraction. $f = 170 \ \text{mm}$.

The dependences shown in figures 4 and 5 have a number of peculiarities. The first of them, consisting in the existence of a minimum value of $P_{th}$, is typical for a plasmatron with long focus lenses [16-19]. The second is that an increase in $P_{th}$ with a decrease in $f$ and almost identical values of $v_0$ for both lenses in the vicinity of the minimum power (see figure 4) is associated with an increase in $r_f$ for a lens with $f = 152 \ \text{mm}$ and approximately the same $z_k$ values. The third feature is visible from the comparison of the dependences in figures 4 and 5 for $f = 170 \ \text{mm}$: the horizontal jet outlet leads to an increase in both the minimum value of $P_{th}$ and $v_0$ in its vicinity. This feature can be associated with the cooling of the discharge by the side gas flow and the necessity to increase these parameters in order to localize the discharge in the caustic region [18].

3.3. Application of coatings

A horizontal extraction of the plasma jet was used. The plasmatron operates on a gas mixture $\text{Ar:H}_2:\text{CH}_4=1:0.07:0.0021$ at atmospheric pressure, the jet is extracted into the atmospheric air. Figure 6 shows an X-ray photograph of a part of the coating surface on a 20 mm x 20 mm tungsten substrate (a) and concentration curves for a fragment including a separate crystal (b). The temperature of the substrate measured by the pyrometer at the edges of the temperature field with a diameter of $\approx 20 \ \text{mm}$ is 1044-1064°C and differs little from the temperature on the field axis.
The emission spectra of the peripheral region of the discharge when operating on the indicated gas mixture contain strong lines belonging to the \( A^2\Pi_g \rightarrow X^3\Pi_u \) transition of the \( \text{C}_2 \) molecule. In paper [20] a substantiation of the role of these molecules in the formation of a diamond coating is given.

Figure 6. Photo of the coating surface (a) and concentration curves for its fragment (b).

4. Automatic system of surface temperature control
The system diagram is shown in figure 7. An image of a fragment of a heated object 1 with the help of a lens 2 is built on the entrance area of an optical fiber 3 and transmitted to the entrance slit of a small-sized spectrometer 5 with a diffraction grating. Mechanical translator 4 is used to change the area of the fragment. In a personal computer 6 with a specially developed program installed, spectra are processed and the temperature measurement results in real time are displayed on the computer monitor and in the form of a binary code at the output connector of unit 7. The maximum system speed is determined by the speed of the spectrometer used and does not exceed 30 ms.

Figure 7. System diagram. 1 is the heated object, 2 is the focusing lens, 3 is the optical fiber, 4 is the mechanical translator, 5 is the small-sized spectrometer, 6 is the personal computer, 7 is the electronic unit with digital temperature display.

The determination of temperature is based on its calculation according to formula (1), in which instead of the ratio of the spectral brightness \( b(\lambda_1, T) \) and \( b(\lambda_2, T) \) of the heated surface, the ratio of the radiation intensities in the spectrum \( I(\lambda_1) \) and \( I(\lambda_2) \) proportional to them is used, which measured for some wavelengths \( \lambda_1 \) and \( \lambda_2 \). Since the emissivity coefficients \( \varepsilon(\lambda_1, T) \) and \( \varepsilon(\lambda_2, T) \) as a rule are not known, they can be excluded in the calculations by setting \( \varepsilon(\lambda_1, T) = \varepsilon(\lambda_2, T) \) when choosing the values \( I(\lambda_1) \), \( I(\lambda_2) \) for close wavelengths \( \lambda_1 \), \( \lambda_2 \). To improve the measurement accuracy, it is possible to find the average temperature value for several pairs of close wavelengths \( \lambda_1 \), \( \lambda_2 \), selected from the interval \( \delta \lambda = \lambda_1 - \lambda_2 < 50 \) nm.

The possibility of excluding emissivity factors is an important advantage of using a spectrometer compared to using two photodiodes with noticeably different the spectral sensitivity regions.

Note that in paper [21] another method is given for eliminating the unknown coefficient \( \varepsilon(\lambda, T) \) when measuring temperature with a spectrometer. It is based on measuring the brightness \( b(\lambda, T) \) and plotting the dependence of \( \ln[\lambda^4 b(\lambda, T)] \) on \( hc/(\lambda kT) \) using the Planck formula in Wien's approximation.
The existence of a linear section on the obtained dependence in a certain wavelength interval indicates the constancy of the coefficient $\varepsilon(\lambda,T)$ in this interval, which does not affect the slope of the section and the value of the temperature determined by the value of the slope.

The system was tested by heating a steel St.3 sample by laser radiation. At a temperature not exceeding the melting point, the readings of the system in the temperature range of (750-950)$^\circ$C coincide with the readings of the thermocouple with an accuracy of 5%. In measurements under the conditions of sample melting, stepwise heating was used with the laser radiation power increasing at each subsequent step. The temperature of 1400$^\circ$C, found for its horizontal section on the dependence of temperature on power, refers to the melting mode and corresponds to the reference data [8].

The system was tested also under conditions of a pilot production with laser powder surfacing. The optical elements of the system were mounted on a device for combined coaxial supply of powder, shielding gas, and laser radiation, mounted on the arm of the robotic manipulator. With an appropriate choice of laser radiation parameters, a melting mode was observed and the measured temperature exceeded the melting temperature of the powder (1350$^\circ$C).

For modern laser 3D technologies, on-line control of powder surfacing or sintering modes is of great importance [22,23]. It allows to detect timely the appearance of defects in the layer and eliminate them by re-scanning the laser beam in the absence of powder, or to change the process parameters when the surface shape deviates from the specified shape. One of these parameters is the intensity of laser radiation. At its constant value, the surface temperature of the formed product increases due to a decrease in the rate of heat removal and when the boiling point is reached a melt splashing can occur [24,25]. Maintaining the temperature value required for melting only can be achieved by introducing feedback into the channel “surface temperature - laser radiation power”. For the development of work in this direction the electronic unit 7 in figure 7 serves.

5. Conclusions
A method of coating deposition with laser irradiation of a gas-dust medium in the form of a free vertical jet of micro-particles in gas was developed. A number of coatings were obtained on various substrates at radiation intensity on 2-3 orders of magnitude lower the intensity at laser ablation of a solid target and increased deposition rate.

A setup with laser plasmatron based on a cw $\ce{CO2}$-laser for the synthesis of diamond coatings has been created. Coatings were obtained on a tungsten substrate when a plasmatron was operated on a mixture of Ar with additions of $\ce{H2}$ and $\ce{CH4}$ and a horizontal extraction of the plasma jet into atmospheric air excluding local heating of the substrate by laser radiation transmitted through the discharge.

The readings of the created system for on-line monitoring the temperature of the heated surface with good accuracy correspond to the results of thermocouple measurements and reference data for the melting temperature. Successful tests of the system have been carried out in a pilot production with laser cladding of metal powder.

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References
[1] Puzryakov A F 2008 Theoretical Basics of Plasma Spraying Technology (Moscow: Bauman Moscow State Technical University Press)
[2] Duley W W 1986 Laser Processing and Analysis of Materials (Moscow: Mir Press)
[3] Glova A F, Lysikov A Yu and Zverev M M 2011 Advanced Materials 10 153
[4] Glova A F, Lysikov A Yu, Nelyubin S S, Peretyatko P I, Ryzhkov Yu F and Turundaevskii V B 2016 J. Phys.: Conf. Ser. 751 012026
[5] Glova A F, Lysikov A Yu, Malyuta D D, Nelyubin S S, Peretyatko P I and Ryzhkov Yu F 2016
Physics of Atomic Nuclei 79 1663

[6] Lebedeva V V 1977 Optical Spectroscopy Technique (Moscow: Moscow State University Press)
[7] Kutateladze S S and Borishanskii V M 1958 Reference Book on Heat Transfer (Leningrad–Moscow: Gosenergoizdat Press)
[8] Kikoin I K 1976 Tables of Physical Quantities (Moscow: Atomizdat Press)
[9] Bondarenko A V, Golubev V S, Dan’shchikov E V et al 1980 SU Academy of Sciences Reports 253 (4) 867
[10] Raizer Yu P 1987 Physics of Gas Discharge (Moscow: Nauka Press)
[11] Fortov V E, Krupak A G, Krupak S A et al 2004 Phys. Usp. 47 447
[12] Khasui A and Morigaki O 1985 Surfacing and Spraying (Moscow: Mashinostroyeniye Press)
[13] Babanov I V, Glova A F and Lebedev E A 1993 Quant. Electron. 23 216
[14] Konov V I and Uglov S A 1998 Quant. Electron. 28 281
[15] Bol’shakov A P, Vostrikov V G, Dubrovskii V Yu et al 2005 Quant. Electron. 35 385
[16] Raizer Yu P 1980 Sov. Phys. Usp. 23 789
[17] Gerasimenko M V, Kozlov G I, Kuznetsov V A and Masyukov V A 1979 Sov. Tech. Phys. Lett. 5 954
[18] Gerasimenko M V, Kozlov G I and Kuznetsov V A 1983 Sov. J. Quant. Electron. 13 438
[19] Raizer Yu P and Surzhikov S T 1984 Sov. J. Quant. Electron. 14 1526
[20] Gruen D V, Zukiier C D, Krauss F R and Pan X J 1995 Vac. Sci. Technol. A. 13 1628
[21] Magunov A N 2009 Instrum. and Experim. Tech. 45
[22] Yau W, Konuk A R, Aarts R et al 2015 J. Mater. Proc. Technol. 220 276
[23] Everton S K, Hirsch M, Stravloulakis P et al 2016 Materials and Design 95 431
[24] Glova A F, Drobyazko S V, Vavilin O I and Shvov E M 2002 Quant. Electron. 32 169
[25] Antonova L I, Gladush G G, Glova A F et al 2011 Quant. Electron. 41 453