Coating formation at laser irradiation of a dusty gas medium

A F Glova, A Yu Lysikov, S S Nelyubin, P I Peretyatko, Yu F Ryzhkov and V B Turundaevskii

State Research Center of Russian Federation Troitsk Institute for Innovation and Fusion Research (SRC RF TRINITI), Moscow, Troitsk, 142190 Russia

E-mail: afglova@triniti.ru

Abstract. A free vertical jet of microparticles in a gas is illuminated by a horizontal focused laser beam. The products of the interaction of particles with radiation are deposited on a heated substrate and form a coating. The substrate is a cathode or an anode at the application of an auxiliary discharge. The parameters of the jet have been calculated and the threshold intensity of laser radiation needed for the evaporation of particles has been estimated. The radiation spectra of the dusty gas medium have been measured and the temperature of particles has been determined. Samples of AlN, Ti, and Ti/AlN coating on steel St.3 have been obtained.

1. Introduction

The service life of parts of machines and mechanisms can be increased by deposition of functional coating with required operating properties on their surfaces. A most important property of coating is their hardness. High hardness is characteristic of binary compounds of light elements with short covalent bonds. Among them are, e.g., AlN, BN, TiN, SiC and some other compounds.

At present time, there are many methods of deposition of coatings. Of particular interest is the laser method. This is due to its relative simplicity and the possibility of evaporating of almost any material for forming coatings. There are reports on preparing of AlN coating by the laser method at irradiation of a solid targets [1,2]. In a number of works coatings are obtained using a combination of laser ablation of target and gas discharge. For example, a discharge with a frequency of 12.45 GHz was used in [3]. This made it possible to decrease the synthesis temperature of AlN on a silicon substrate surface to lower than 80°C at laser ablation of pure Al in a nitrogen atmosphere at a pressure of 2·10^{-4} mmHg by radiation of second harmonic of a Nd:YAG laser. It should be noted that the role of auxiliary gas discharge in those and other experiments is not completely understood and further studies are necessary. Actually, existence of the discharge changes the ion composition of the plasma and the velocity of ion movement near the surface; microfragments outgoing from the target surface that were not evaporated during the ablation take a positive charge due to the thermal emission or a negative charge due to the charge with plasma electrons and, therefore, they participate in the drift movement and in plasmachemical reactions in the volume and on the surface, etc.

We propose a method of deposition of coating by laser ablation of particles of a dusty gas medium that also makes it possible to evaporate almost any material, like the method of laser ablation of solid targets. In this case, the power and the power density of laser radiation can be noticeably decreased, since the energy losses of laser radiation by particles are lower than the losses in the case of irradiating a solid target. A flow of charged particles directed to the substrate can be formed in an electric field or...
in a gas discharge which in combination with the flow of heated particles that take velocities of reactive motion as a result of partial evaporation, can increase the deposition rate as compared to the rate of deposition from a gaseous phase during ablation of a solid target.

The aim of this work is to study the possibility of obtaining coating on metallic substrates using the method of ablation of particles of a dusty gas medium in a form of free vertical jet of microparticles in a gas when the jet is irradiated by a horizontal laser beam.

2. Experimental setup

The schematic of the experimental setup is shown in figure 1. A focused beam 1 enters into interaction chamber 3. Weigher 4 is filled with a powder of depositing material or a powder mixture and forms a dusty gas medium as a free vertical jet of microparticles 5 in a gas at a controlled pressure. Products of interaction of the particles with radiation in interaction region 6 are deposited on substrate 7 and form a coating. Auxiliary electrode 8 is used to study the influence of a dc electric field or a dc glow discharge on the deposition process. The substrate and the electrode have central holes for transmitting the beam. A part of the laser radiation passes through the interaction region 6 and with the help of mirrors 9 and 10 is used to heat the substrate. We used steel St.3 substrates 20 mm in diameter and 1.5 mm in thickness. The preliminary preparation of their working surfaces was carried out by chemical etching or by quartz sand jet.

![Figure 1. Schematic of the experimental setup.](image)

The experiments were performed using a fiber Yb laser with radiation wavelength $\lambda = 1.07 \, \mu m$ and the maximum radiation power of 2 kW. The laser can operate in cw, pulse or pulse-periodic mode with varying pulse duration and pulse repetition rate. The laser radiation is multimode. As a multimode laser radiation is focused, the effective beam radius $w(z)$ at the distance $z$ on both sides from the focal plane ($z = 0$) is described by the expression

$$w(z) = 2\text{BPP} \frac{F}{D} \left[ 1 + \left( \frac{z}{4\text{BPP} \left( \frac{D}{F} \right)^2} \right)^2 \right]^{1/2}, \quad (1)$$

where $F$ is the lens focal length, $D$ is the output laser beam diameter, BPP = $D\gamma/2$ is the beam quality, $\gamma$ is the radiation divergence. Radiation intensity $I_0$ averaged over a spot with radius $w(z)$ is

$$I_0 = \frac{\Delta \delta W}{\pi w(z)^2}, \quad (2)$$

where $W$ is the radiation power, $\delta = 0.86$ is the power fraction in a spot, and $\Delta = 0.792$ is the power loss for reflection from the optical elements. For caustic length we have

$$z_k = 8\text{BPP} \left( \frac{F}{D} \right)^2. \quad (3)$$
As the lens focus length increases the caustic length increases markedly and this makes it possible to decrease requirements to the accuracy of the lens placing with respect to the jet. In accordance with our data (BPP = 2 mm⋅mrad, D = 10 mm) $z_k = 45 \text{ mm}$ for $F = 53 \text{ cm}$ and $z_k \gg d_c$ where $d_c = 5 \text{ mm}$ is the jet diameter.

3. Parameters of the dusty gas medium

3.1. The initial velocity of motion and the density of particles in jet

The main parameters of a microparticle jet in the absence of laser irradiation are the velocity of particle motion and the density or the number of particles in the interaction region. To estimate these parameters, we will consider a particle as a sphere with radius $r$. Velocity $v$ of the vertical motion of a particle without collisions with other particles can be found from the solution of equation $\frac{dv}{dt} = g - a v$ where $g$ is the acceleration due to gravity, $a = 6\pi \eta r/m$, $\eta$ is the gas dynamical viscosity, and $m$ is the particle mass. Figure 2 shows the results of calculations of the dependence of $v$ on $r$ for three values of $h$ for Al particles moving in nitrogen at normal conditions at the initial condition $v = 0$ (here $h$ is the distance from the weigher outlet to the laser beam axis). Comparatively coarse particles ($r > 30 \mu\text{m}$) demonstrate noticeable difference in dependences $v(h)$ at a fixed radius, since the velocities of such particles are still far from the constant velocity limit at the chosen $h$. The results of calculation for other pressures will be slightly different from the results shown in figure 2, because of a weak pressure dependence of the dynamic viscosity of the gas [4].

The density of particles with almost the same size in a given cross section of the jet with area $S_c$ can be estimated from their flow rate $G$ using relationship $n_p = G/(mv_S c)$. For the interaction region, we have $S_c = \pi d_c^2/4$. Because the interaction region volume is also known ($V \approx \pi w(z)^2 d_c$), the number of particles in the region will be

$$N_p = n_p V. \tag{4}$$

Figure 3 shows the results of calculations of $N_p$ as a function of $r$ at $h = 3.5 \text{ cm}$, $d_c = 5 \text{ mm}$, $w(z) = 0.23 \text{ mm}$ and $G = 20 \text{ mg/s}$ typical in the experiments.

3.2. Temperature of particles

The irradiation of a jet by laser radiation results in the formation of bright illumination in the interaction region with sizes that noticeably larger than the geometric size of the interaction region. The illumination center is slightly shifted along the beam with respect to the jet axis. The spectrum measurements were performed in the wavelength range of 400-800 nm. The radiation was focused by a lens with focal length $F = 53 \text{ cm}$. The initial laser radiation intensity in a spot with radius $w(z) = 0.23 \text{ mm}$ was $I_0 \approx 7 \times 10^5 \text{ W/cm}^2$, $h = 3.5 \text{ cm}$; the nitrogen pressure in the interaction chamber was $p_{N_2} = 1.5$ or 100 mmHg.
A feature of the measured spectra was the increase in the spectral brightness of illumination with the wavelength. The spectra of compounds such as AlN and B$_4$C are quite smooth at the irradiation conditions noted (figure 4), the spectra for Ti and TiC particles have clear bands and individual lines. The smooth spectra are more preferable to determine the temperature of particles of the dusty gas medium, since they can be interpreted using the standard formula for the Planck spectrum (e.g., [5]).

The temperature was calculated in the assumption that the emissivity factors are independent of the wavelength. The temperatures found at $p_{N_2} = 1.5$ mmHg for AlN and B$_4$C particles were 2470 K ± 15% and 2770 K ± 15%, respectively. The fact that, at the same irradiation conditions, the temperature of B$_4$C particles is higher seems to be due to the difference in the radiation absorption coefficient: the B$_4$C powder is darker than the AlN powder. Note that, at $p_{N_2} = 100$ mmHg, the spectra for AlN and B$_4$C particles are similar to the spectra shown in figure 4, and the temperature is within the limits of the measurement error.

With allowance made for the measurement accuracy, the maximum temperature for AlN particles is 2840 K and close to the evaporation temperature of AlN (2790 K). Because of this, it is interesting to estimate the intensity of the laser radiation required to evaporate these and other particles in the dependence on their radii and to compare it with fixed value $I_0 \approx 7 \times 10^5$ W/cm$^2$ chosen during the measurements.

![Figure 4.](image)

**Figure 4.** Dependences of the spectral brightness $b$ on the wavelength for AlN (a) and B$_4$C particles (b) at $p_{N_2} = 1.5$ mmHg.

### 3.3. Evaporation of particles

#### 3.3.1. Threshold intensity for evaporation

The threshold intensity of particle evaporation by laser beam was estimated using a simplified equation of energy balance of a particle

$$ASI, \delta t = m(Q_m + Q_v + cT_v) + \delta t(\sigma A S T_v^4 + a_T S T_v),$$

where $A$ is the absorption ability of a material, $S$ is the surface area of a particle, $I_t$ is the threshold intensity of evaporation, $T_v$ is the evaporation temperature, $Q_m$ is the specific melting energy, $Q_v$ is the specific evaporation energy, $\sigma$ is the Stephan-Boltzmann constant, $a_T$ is the heat loss coefficient and $\delta t = 2w(z)/v$ is the flying time of a particle through the interaction region. The heat loss coefficient was calculated using the expression for laminar flow of spherical bodies taken from [6]. The model used does not take into account the change in particle mass during its evaporation and the change in $\delta t$, and actually gives the upper estimation of the intensity.

The calculations were performed for Ti, AlN and B$_4$C particles at $w(z) = 0.23$ mm, $h = 3.5$ cm, $p_{N_2} = 1.5$ mmHg and $A = 0.3$ that is the same for all particles. Figure 5 shows the results of calculating $I_t$ as a function of $r$. The dependences show that the intensity $\sim 5 \times 10^5$ W/cm$^2$ is required to evaporate an AlN particle $\sim 50$ µm in diameter. This intensity is lower than $I_0 \approx 7 \times 10^5$ W/cm$^2$, and we can expect that such particles will be evaporated in the radiation field with intensity $I_0$, which corresponds to the results of measuring the temperature of AlN particles.
3.3.2. Criteria of optical breakdown. It is known that compound AlN decomposes at the evaporation temperature. Al vapors have a low ionization potential 5.98 eV, and their presence in the interaction region can favor the optical breakdown in the region. The thermal explosion model [7,8] gives a good agreement of the breakdown thresholds near a solid target with the measured results. We use the main statements of the model to determine the possibility of the optical breakdown in our conditions.

To estimate the threshold coefficient of laser radiation absorption \( \alpha_{th} \) and the time of transition of gas to a high-temperature state \( \tau_{tr} \), we use the following expressions [9]

\[
\alpha_{th} = \frac{\lambda_1 T_1}{I_0^2 (1 + R) \alpha_0^2},
\]

\[
\tau_{tr} \approx \frac{c_1 \rho_1 T_1}{(1 + R) I \alpha_{th}},
\]

where \( T_1 \) is the vapor temperature, \( \lambda_1 \) is the thermal conductivity coefficient of vapor, \( c_1 \) and \( \rho_1 \) are the heat capacity and the density of vapor, respectively, \( r_0 \) is the size that determines the heat loss, \( R = 1 - A \) is the reflectivity, \( \alpha_0 = \frac{\text{dln} \alpha}{\text{dln} T} \). At \( T_1 = 3000 \text{ K}, I = I_0 \approx 7 \cdot 10^5 \text{ W/cm}^2, r_0 = w(z) = 0.23 \text{ mm}, A = 0.3, \alpha_0 \approx 10 \), taking for Al vapors \( \lambda_1 \approx 10^{-3} \text{ W/(cm} \cdot \text{K)}, c_1 = 0.78 \text{ J/(g} \cdot \text{K}) \) and \( \rho_1 = 1.2 \cdot 10^{-4} \text{ g/cm}^3 \), we have \( \alpha_{th} \approx 5 \cdot 10^{-4} \text{ cm}^{-1} \) and \( \tau_{tr} \approx 4.7 \cdot 10^{-4} \text{ s} \).

The breakdown is possible as two conditions are fulfilled as follows. First, time \( \tau_{tr} \) must be smaller than the flying time of a particle through the interaction region \( \delta t = \frac{2w(z)}{v} \). According to figure 2, \( \delta t = 2 \cdot 10^{-3} \text{ s} \) for particles 50 \( \mu \text{m} \) in size, and inequality \( \tau_{tr} < \delta t \) obeys. In this case, the vapor temperature \( T_1 \) is close to particle temperature \( T \). Second, the coefficient of absorption of laser radiation \( \alpha \) must be higher than the threshold value. The calculations by formulas from [10] showed that the coefficient of absorption of laser radiation with wavelength 1.07 \( \mu \text{m} \) in a thermal plasma of Al vapors at the atmosphere pressure and a temperature of 3000 K is \( \alpha \approx 10^{-7} \text{ cm}^{-1} \ll \alpha_{th} \approx 5 \cdot 10^{-4} \text{ cm}^{-1} \), which indicates the absence of the optical breakdown.

![Figure 5](image1.png)

**Figure 5.** Dependences of \( I_v \) on \( r \) at \( w(z) = 0.23 \text{ mm, h = 3.5 cm, } p_{N_2} = 750 \text{ mmHg and } A = 0.3 \).

3.3.3. Reactive motion of particles. Reactive acceleration of the particles under action of laser radiation was theoretically studied in detail for the first time in [11]. Standard geometry of coating deposition from the particle jet formed by a coaxial nozzle was considered. The particle collisions were not taken into account in the calculations. It was shown that stainless steel particles 45 \( \mu \text{m} \) in diameter can take additional velocity of \( \approx 100 \text{ m/s} \) due to the action of the vapor recoil momentum at the mean radiation intensity \( \approx 10^3 \text{ W/cm}^2 \).

In the case of our experiments when the jet is irradiated in a crossed geometry, the collisions must be taken into account, which will influence the mean particles velocity. A qualitative justification of the effect of reactive particle acceleration can be the mentioned above shift of the center of the illuminating region with respect to the jet axis along the laser beam.
4. Formation of coatings and their properties

In all our experiments, the laser radiation output power $W$, lens focus length $F$, focal spot radius $w(z)$, initial intensity averaged over the spot $I_0$, radiation pulse duration $\tau$, and distance $h$ were unchanged and were 2 kW, 53 cm, 0.23 mm, $7 \times 10^3$ W/cm$^2$, 50 ms, and 3.5 cm, respectively.

4.1. AlN coating

Figure 6 shows the photographs of coating on etched substrates of St.3 obtained by irradiation of AlN particles at $p_{N_2} = 1.8$ mmHg and pulse repetition rate $f = 0.5$ Hz. The substrates shown in figures 6a and 6b were the anode and the cathode, respectively (discharge current $I_d = 10$ mA, distance between electrodes $d = 20$ mm, distance between the substrate and the jet axis $d_l = 10$ mm); the substrate shown in figure 6c was used without discharge at $d_l = 10$ mm. The substrates were preliminarily (without a jet) heated by laser, and the substrate-cathode was also additionally heated in a discharge for the same time 100 s. The weigher was immediately turned on after the preliminary heating, the substrate was additionally heated during time $t = 60$ s. After the complete heating cycle, the total increase in the substrate temperature $\Delta T_s$ with respect to room temperature (20$^\circ$C) slightly differed from the heating at the end of the preliminary stages and were $\Delta T_s = 350$, 385 and 350$^\circ$C for the substrates shown in figures 6a, 6b and 6c, respectively.

Figure 6. The photographs of coating on etched substrates of St.3 for substrate-anode (a), substrate-cathode (b) and substrate without discharge (c).

The X-ray diffraction spectra of the coatings showed only lines groups of AlN, $\alpha$-Fe and Fe$_3$O$_4$; the latter two groups seem to belong to the substrate base metal.

The coatings shown in figure 6 are substantially different from each other in their adhesion properties. Quantitative measurements were not performed here. It can be only noted that the coating on the substrate-anode is hardly removed by a metallic needle with a small rounding radius. The reason can be that the dusty particles can be charged by plasma electrons in the discharge plasma [12] and can take additional velocity during their motion under action of an accelerating potential to the substrate-anode. According to [13], the increase in the particle velocity during depositing on the substrate improves the adhesion of the coating to the substrate. Let us perform a numerical estimation. Neglecting collisions between particles, we have the particle velocity $v_p = 0.9[qU/(\rho r^2)]^{1/2}$ cm/s (here, $q$ is the particle charge in the elementary charge unit, $U$ is the potential, V; density $\rho$, g/cm$^3$; radius $r$, $\mu$m). For AlN particles 1-5 $\mu$m in radius, we find that $v_p \approx 22-2$ m/s at $U = 200$ V and $q \sim 10^3$.

Note, that we did not obtain good adhesion when non-etched substrate-anode was used at the same $p_{N_2}$, $f$, $I_d$ and $d$, even we changed temperature and distance $d_l$ (the experiments were performed at $\Delta T_s = 510^\circ$C, $d_l = 10$ mm and $\Delta T_s = 310^\circ$C and $d_l = 3$ mm).

Another mechanism of accelerating particles is the acceleration under action of vapor recoil momentum. To determine the possibility of action of this mechanism, the substrate-cathode was mounted in the place of the auxiliary electrode (position 8; figure 1) and the electrode-anode that becomes the auxiliary electrode is placed in position 7. The distance from the substrate to the jet center is 5 mm, $d = 20$ mm and other parameters being unchanged. We used a non-etched substrate; its heating and the preliminary cleaning its surface were performed in a discharge. The value $\Delta T_s \approx 400^\circ$C is approximately the same as that for the substrate-cathode in figure 6b (385$^\circ$C). Unlike the substrate shown in figure 6b, these experiments demonstrated good adhesion of the coating to the substrate, despite the slowing-down of negatively charged particles in the discharge by the cathode electric field.
It can be noted that the results presented in this Section completely correspond to well-known facts [13,14]: a preliminary preparation of the substrate surface and quite high velocity of particle motion to the substrate are necessary conditions of obtaining required adhesion of a coating to a substrate.

### 4.2. Ti coating

Figure 7 shows the photographs with different magnification of a coating obtained by deposition of Ti particles irradiated by laser on an etched steel St.3 substrate-anode. The coating was deposited at the following conditions: \( p_{N_2} = 1.5 \text{ mmHg}, f = 1 \text{ Hz}, d = 20 \text{ mm}, d_1 = 10 \text{ mm}, \) deposition time \( t = 50 \text{ s}, \Delta T_s = 300\,^\circ\text{C} \). The X-ray diffraction spectra were contained only \( \alpha\)-Ti lines and also \( \alpha\)-Fe lines belonging to the substrate base metal. It is likely that the TiN compound did not form because of high (3280\,^\circ\text{C}) evaporation temperature of titanium and insufficient intensity of laser radiation for titanium to be evaporated. In figure 7a, bright points are like to solidified titanium droplets. The droplet can have a form of rings or droplets with a valley in the center surrounded with finer rings (figure 7b). The coating has a strong adhesion with the substrate, and it can be considered as the titanium facing on steel St.3 obtained in our conditions.

![Figure 7. The photographs with different magnification of Ti coating on an etched steel St.3 substrate-anode.](image-url)

Similar experiments were performed with a substrate that was subjected to sand-blasting. The difference for the conditions of deposition on the etched substrate was that we changed nitrogen pressure and turned on or did not turn on a discharge. In the case as \( p_{N_2} = 1.5 \text{ mmHg} \) and the discharge was turned on, the adhesion improved as compared to the adhesion obtained without discharge, but it was weaker than that on an etched substrate deposited with discharge. The increase in the nitrogen pressure to 15 mmHg during deposition without discharge insignificantly influences the coating adhesion and does not change the X-ray diffraction spectrum. At both nitrogen pressures, the X-ray diffraction spectra contained \( \alpha\)-SiO\(_2\) lines, along with \( \alpha\)-Ti and \( \alpha\)-Fe lines. It seems likely that the \( \alpha\)-SiO\(_2\) lines are due to quartz-sand particles that on the substrate surface during its sand-blasting. It seems likely that the existence of a sublayer of sand particles decreases the coating adhesion.

Thus, the experiments on deposition of Ti coating confirmed the positive influence of an auxiliary discharge on the adhesion properties of the coating and the influence of the method of preliminary preparation of a substrate on these properties.

### 4.3. Coating deposited by laser irradiation of a Ti and AlN particle mixture

At present, composite coatings attract significant interest, since such coatings can have high technological properties. Composite coatings are usually prepared from composite powders in which each of composite particles contains all initial components with desired properties [14].

An Al/AlN composite coating was prepared in [15] by plasma sputtering of a mixture of Al and AlN powders. The coating was a solidified layer of molten Al with embedded AlN particles. The coating combines two desired properties: high adhesion of Al melt to the substrate and high hardness due to the presence of AlN particles.

A jet containing a mixture of Ti and AlN particles with volume proportions Ti:AlN=3:1 or 1:1 was irradiated by laser beam at nitrogen pressure 1.5 and 4.5 mmHg. The substrate temperature was varied within 290-340\,^\circ\text{C}, and auxiliary gas discharge was not used. We used substrates subjected and not
subjected to sand-blasting. No adhesion was observed in the case of untreated substrates; in the case of the sand-blasted substrates washed by ethanol, the adhesion was better than that for unwashed substrates, but it was insufficient for practical applications.

Figure 8 shows the photographs with various magnification of the coating on the substrate of steel St.3 treated by sand-blasting obtained by laser irradiation of the Ti:AlN=3:1 particle mixture at $p_{N_2} = 1.5$ mmHg, $t \approx 100$ s and $f = 1$ Hz. At figure 8, as compared to figure 7, the density of bright points and their size are smaller. The results of measurements of the X-ray diffraction spectra of the coating were ambiguous. While $\alpha$-Fe and $\alpha$-SiO$_2$ lines exist in all the spectra, the Ti and AlN lines are absent in the spectrum of the substrate, shown in figure 8, but the lines appeared, e. g., as the deposition time decreases and the pressure increases ($t = 30$ s and $p_{N_2} = 4.5$ mmHg, respectively) at the constant ratio Ti:AlN=3:1. The absence of Ti and AlN lines in the spectra can be due to formation of the Ti/AlN solid solution on the surface or its part by a mechanism similar to that proposed in [15]. The element analysis of the solid solution was not carried out.

![Figure 8](image)

**Figure 8.** The photographs with various magnification of the coating on the steel St.3 substrate treated by sand-blasting without discharge.

5. Conclusions
As a result of this work, we designed the experimental unit for producing coatings on structural materials using irradiation of a dusty gas medium in the form of free vertical jet of microparticles in gas by horizontal laser beam. The main parameters of the medium were determined, and the temperature of irradiated particles was measured. We prepared AlN, Ti and Ti/AlN coating on substrates of steel St.3, determined the role of auxiliary gas discharge and the method of preliminary preparation of substrates.

The results can be used for development of basis of the technology of producing coating by this method.

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References
[1] Szekeres A, Cziraki A, Huhn G, Havancsak K, Vlaikova E and Socol G 2012 *J. Phys.: Conf. Ser.* **356** 012003
[2] Jagannadham K, Sharma A K, Wei Q, Kalyanraman R and Narayan J 1998 *J. Vac. Sci. Technol. A* **16** 2804
[3] Sun J, Wu J D, Ying Z F, Shi W, Zhou Z Y, wang K L, Ding X M and Li F M 2001 *Appl. Phys. A* **73** 91
[4] Kikoin I K 1976 *Tables of Physical Quantities* (Moscow: Atomizdat)
[5] Lebedeva V 1977 *Optical Spectroscopy Technique* (Moscow: Moscow State University Press)
[6] Kutateladze S S, Borishanski V M 1958 *Reference Book on Heat Transfer* (Leningrad–Moscow: Gosenergoizdat)
[7] Nastoyashchii A F 1980 *Sov. J. Quant. Electron.* **10** 95
[8] Vedenov A A, Gladush G G, Yavokhin A N 1981 Sov. J. Quant. Electron. 11 896
[9] Bondarenko A V, Golubev V S, Dan’shchikov E V et al 1980 SU Academy of Sciences Reports 253 (4) 867
[10] Raizer Y P 1987 Physics of Gas Discharge (Moscow: Nauka)
[11] Kovaleva I O, Kovalev O B 2012 Opt. Las. Technol. 44 714
[12] Fortov V E, Khrapak A G, Khrapak S A, Molotkov V I, Petrov O F 2004 Phys. Usp. 47 447
[13] Khasui A, Morigaki O 1985 Surfacing and Spraying (Moscow: Mashinostroyeniye)
[14] Puzryakov A F 2008 Theoretical Basics of Plasma Spraying Technology (Moscow: Bauman Moscow State Technical University Press)
[15] Shahien M, Yamada M, Yasui T, Fukumoto M 2011 Coatings 1 88-107