On the influence of the condensed particles on the absorption properties of plasma created by ablation controlled arc in a capillary

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Abstract. The results of experimental studies of the absorption properties of plasma created by ablation controlled arc in a capillary are presented. It is shown that the dominant influence on the plasma absorption properties is exerted by condensed particles formed in relatively low-temperature zones in the vicinity of the capillary wall and on the periphery of the plasma jet, whereas the plasma bremsstrahlung is optically thin. The nonmonotonic behavior of the plasma optical thickness in the spectral range \( \Delta \lambda = 400-700 \, \text{nm} \), as well as amplification of the probing radiation in a relatively narrow wavelength interval \( \Delta \lambda = 628 \pm 5 \, \text{nm} \), caused, probably, by resonant excitation of condensed particles by electromagnetic radiation, are detected. The estimations of the condensed particles parameters (the average size \( d_D \approx 2-4 \, \text{nm} \), the concentration \( N_D = (1-5) \cdot 10^{13} \, \text{cm}^{-3} \), the volume fraction \( f_V \approx (0.1-3) \cdot 10^{-6} \)), which quantitatively consistent with the results of studies of the microstructure of the condensed phase on scanning electron microscope, have been obtained.

1. Introduction
A pulsed discharge in a capillary with an ablating wall is one of the methods for obtaining a highly ionized dense plasma [1,2]. This type of discharge is of interest for many practical applications (this question is discussed elsewhere [3]) due to the possibility of obtaining a plasma of the required chemical composition over a wide range of pressures, temperatures, density of charged particles due to fairly simple procedures: selecting the type and method of supplying the working fluid, and selecting the parameters of the discharge pulse. One of distinctive features of such a discharge is the spatial separation into a high-temperature paraxial zone and a relatively low-temperature periphery with substantially different component composition. On the site of the plasma jet, this separation is caused by high temperature gradients and thermal and barodiffusion processes that promote the localization of light elements (electrons, hydrogen ions) in the central high-temperature zone and the displacement of heavy elements to the periphery [4]. Inside the capillary, in addition to above mentioned mechanisms, the spatial separation of the discharge is largely determined by the wall ablation and subsequent dynamics of the evaporated substance, a significant portion of which is carried away from the capillary through a relatively cold near-wall layer. The near-wall layer plays an important role in the balance of mass and energy [5–7], and its cross section is comparable to the area occupied by the high-temperature plasma located in paraxial zone [8,9]. According to the estimates [6,8,9], the temperature in the near-wall layer is \( T = 3000-5000 \, \text{K} \) that promotes optimal conditions for the formation of polyatomic molecules and condensed particles [10,11]. The main source of condensed particles is carbon atoms, contained in the capillary wall substance. The presence of condensed particles can
significantly affect the properties of erosion plasma and have far-reaching consequences for practical applications.

Despite the large number of works devoted to the study of capillary discharge with an ablating wall, the questions concerning the condensed particles formation and their influence on the plasma properties remain unexplored. Therefore, the main purpose of this work was to establish the presence of condensed particles in the capillary discharge plasma, to evaluate their main parameters (characteristic size, concentration) and to obtain data on their spatial distribution and temporal dynamics. The extinction method [12] and scanning electron microscopy were used to study these problems. With the help of these methods, data on the optical thickness of the plasma ejected from the capillary into the air atmosphere were obtained and the structure of the condensed phase was studied in detail.

2. The object of research and the procedure for determining the optical thickness of plasma

The formation and outflow of a plasma jet into a submerged space is a non-stationary process, which can be conditionally divided into four stages: ignition of the discharge, initial, quasistationary stage and relaxation stage. The structure of the flow is formed finally to the beginning of the quasistationary stage. A steady-state regime of the wall's ablation is established until this moment of time, the decomposition products of which completely displace the ambient gas from the capillary [4]. The flow scheme and the image of the plasma jet corresponding to the quasistationary stage are shown in figure 1. The contact surface 7, formed as a result of the deceleration of the jet and separating the outflowing plasma from the unperturbed gas of the surrounding atmosphere, is observed distinctly with the help of shadow methods. The bright glow region 5 of almost cylindrical shape is present in the near-axis zone (figure 1(b)). Plasma moves at high speed and is characterized by high temperature and density of charged particles in this region. At the initial section of the jet, this region is heated up by outflow currents closed on the external electrode 3. The boundary 6 of the high-temperature region 5 corresponds to the zone of large temperature gradients and plasma density. The temperature decreases by more than 2 times, and the density of charged particles decreases by more than an order of magnitude at the boundary of this region if to compare with paraxial zone [4]. During the quasistationary stage, the volume restricted by the contact surface is filled by the plasma flowing out from the capillary. This volume continues to exist even after the discharge termination - during the relaxation stage, - the duration of which can reach several tenths of a second.

The wall of a capillary gap is made from hydrocarbon polymer - polymethylmethacrylate, - whose chemical formula C5H8O2 determines initial stoichiometric composition of plasma. The initial diameter and the depth of a capillary are respectively d=1 mm and h=5 mm. The anode is tightly mounted to the capillary inlet and the cathode is placed in the vicinity of the capillary outlet (figure 1).

A capacitive storage device connected to the spark gap through the time-setting inductance is used as a power source. The algorithm of discharge power supply roughly corresponds to the sine half-wave. Following parameters of discharge pulse are typical for used power supply: the stored energy Q=80 J, the amplitude of discharge current Im=70 A, duration of discharge pulse T=9 ms. More detailed information regarding the design of the capillary gap and electrical system circuit can be found elsewhere [4]. The parameters of the discharge pulse are chosen in such a way as to provide a laminar flow regime of the plasma jet, in which the flow structure is retained over a sufficiently long section, which is an important condition for ensuring the repeatability of the results of optical measurements. In this series of experiments, the main attention was focused on studying the absorption properties of the initial section of a plasma jet with typical length and width up to 40 mm and 10 mm respectively, on which the features of the flow structure are pronounced most clearly. This section is marked in figure 1(b) as probing area 9.

The optical thickness τ of probing area is determined from relation

$$\tau = \ln \frac{I_0}{I},$$
where $I_0$, $I$ – the intensity of incident and transmitted radiation, respectively. The intensity of transmitted radiation is determined as difference between total radiation $I_\Sigma$, emitted by plasma and probing source, and radiation from plasma $I_{pl}$, i.e. $I = I_\Sigma - I_{pl}$. The optical thickness averaged over the line of sight is determined in this case. Its value is connected with the averaged absorption coefficient $\alpha$ by the dependence

$$\tau = \alpha \cdot \Delta x,$$

where $\Delta x$ – thickness of the absorption layer.

**Figure 1.** (a) The flow scheme and (b) the image of the quasistationary stage of the plasma jet ejected into the air atmosphere ($p=1$ bar): (1) internal electrode (anode), (2) capillary, (3) external electrode (cathode), (4) cathode torch, (5) paraxial zone, (6) jet boundary, (7) contact surface, (8) jet’s front, (9) probing area.

Schematic diagram of the optical measurements including the basic elements is represented in figure 2. Depending on the problem to be solved, various types of radiation sources and registration devices were used in experiments.

The narrow-beam radiation source - the helium-neon laser LGN-207A ($\lambda = 632$ nm, $N = 2$ mW) - was used to study the temporal dynamics of the optical thickness in the local zone of the investigated region. In these experiments, the laser radiation was focused at the center of the investigated region. The angle of rays deflection provided by the focusing lens 2 (figure 2) did not exceed $2^\circ$, which made it possible to provide a small transverse dimension of the beam (less than 0.5 mm) throughout the probed section. Then, the transmitted radiation with the help of lens 5 was focused at the receiving part of the registration device – the cathode of the photomultiplier FEU-68, or the CCD matrix of the Motion Pro N3 high-speed video camera. The diaphragm 4 and the system of filters 6, 7, which were placed between the plasma and the recording device, used for attenuation the plasma intrinsic radiation. The electric signal output from the photomultiplier was fed to the input of a digital oscilloscope Rigol DS1000B. The use of a video camera in addition to photomultiplier was caused by
the necessity to check the possible influence of the probing beam refraction on optical inhomogeneities on the magnitude of the electrical signal recorded by the FEU-68. This problem can arise because variable sensitivity of the photocathode surface in the case if a sufficiently strong shift of the beam, projected onto the receiving surface of the photomultiplier, takes place. The registration of a laser spot on the CCD-matrix of a Motion Pro N3 high-speed video camera (frame rate up to 200,000 fps) allows us to estimate the influence of this effect by tracking the spot trajectory. As a result of numerous experiments it was established that the maximum displacement of the laser beam position on the surface of CCD-matrix does not exceed 0.3 mm and does not introduce a significant error in the value of the electric signal registered by the FEU-68. Processing of a sequence of frames with the help of a specially developed soft makes it possible to obtain temporal dependences of the radiation intensity recorded on a Motion Pro N3 video camera. Obtained in such a manner the time dependences of optical thickness are qualitatively and quantitatively consistent with the oscillograms of electrical signals recorded from the output of the photomultiplier.

![Figure 2. Schematic diagram of optical measurements: (1) source of probing radiation (laser, ribbon tungsten lamp), (2), (5) lenses, (3) probing object, (4) diaphragm, (6), (7) neutral and interference filters, (8) registration device (photomultiplier, high-speed video camera Motion Pro N3, fast camera Andor iStar together with spectrograph MS-257).](image)

The source of continuous radiation - a ribbon tungsten lamp - was used to study the spatial distribution of optical thickness. In this scheme, the sharp image of ribbon was projected at the selected section of the investigated region and then projected at the entrance slit of the MS-257 spectrograph (slit width δ=50 μm, diffraction grating 1800 grating/mm). The 2D-spectra were recorded by the Andor iStar fast camera (minimum exposure time 100 ns) placed in the output plane of the MS-257 spectrograph. The recorded 2D-spectra of tungsten ribbon lamp radiation, plasma radiation, as well as the total radiation of the plasma and the transmitted radiation of the tungsten ribbon lamp, were used for plotting the radial profiles of optical thickness in different sections of the plasma jet. At the same time, we used free from line radiation spectral intervals for plotting the optical thickness profiles, namely: \(\Delta\lambda=445-451\) nm, \(\Delta\lambda=520-530\) nm, \(\Delta\lambda=622-645\) nm, \(\Delta\lambda=722-730\) nm. This choice makes it possible to eliminate the influence of absorption in lines and to enhance the effects associated with continuous radiation and the condensed phase.

3. The results of measuring the optical thickness

It was found in experiments that the strongest change in optical thickness during the quasistationary stage is observed in the volume located in the vicinity of the initial section of the plasma jet (this volume is marked as 9 in figure 1). The dimensions of this volume in the longitudinal and transverse directions are respectively \(\Delta z \approx 30\) mm and \(\Delta d \approx 6-10\) mm. During the relaxation stage this volume expands up to the boundary of the contact surface. The radial profiles of the optical thickness on the initial section of the plasma jet are substantially non-monotonic and characterized by a deep dip in the high temperature paraxial zone and by a maximum at the peripheral region (figure 3). The optical thickness of the peripheral zone reaches \(\tau=k_\nu\Delta x \approx 0.3\), that, taking into account the effective thickness of the absorbing layer \(\Delta x=3-5\) mm, gives the value of the absorption coefficient \(k_\nu=0.6-1\) cm\(^{-1}\). As will
be shown below, the main contribution to the absorption of radiation is provided by nanoscaled particles of the condensed phase. So, the revealed features of the radial profiles of optical thickness indicate the absence of condensed particles in the high-temperature paraxial zone and their concentration at the periphery of the jet.

![Optical thickness and Intensity](image)

**Figure 3.** (1) The radial profiles of the optical thickness and (2) the radiation intensity of the plasma jet in a section located at a distance \( z = 2.5 \) mm from the capillary outlet: the wavelength of the probing radiation is \( \lambda = 525 \) nm, the diameter of the capillary is \( d = 1 \) mm, the moment of time after the discharge ignition is \( t = 4 \) ms.

Additional information on the state of the condensed phase was obtained by analyzing the time dependences of the optical thickness obtained in local zones of a plasma jet probed by a narrow laser beam. Examples of such dependencies for two discharge modes are shown in figure 4. In general, the course of optical thickness tracks the change of the condensed phase parameters (concentration and particle sizes), the dynamics of which in a given spatial domain is determined by the prehistory of processes depended on the parameters of discharge pulse (primarily on the discharge power density), starting from the moment of the capillary wall ablation and finishing by the establishing the temperature distribution. So, it is quite expected that the course of the optical thickness in the probed spatial domain depends on the discharge power density and can vary noticeably along and across the jet. However, the unexpected was the fact that not only the absorption, but also the amplification of the probing radiation took place at the radiation wavelength of helium-neon laser (curve 2 in figure 4). It should be noted that this effect was firstly mentioned in [13] and up to date has not found a satisfactory explanation. However, despite the variety of the optical thickness courses, the general trends are detected clearly. In particular, a sharp change in the optical thickness is observed at the beginning and at the end of the quasistationary stage. In the first case, it happens because establishing an equilibrium mode of the wall ablation and the arrival of condensed particles into the probed spatial domain, and in the second case - due to a decrease in the flux density of the condensed particles in accordance with discharge power algorithm. Thus, complete restoration of the optical properties of the probed region occurs after the relaxation stage, the duration of which reaches up to several tenths of a second. These features make us possible to estimate the velocity of a substance in the peripheral zone, whose magnitude reaches 10 m/s during the quasistationary stage, and decreases to less than 1 m/s after the discharge termination. Thus, the velocity of the substance in the peripheral zone is for 3-5 times lower than the velocity of the front of plasma jet (30-50 m/s) and for 2-3 orders lower than the plasma flow velocity of on the capillary outlet cross-section (0.5-3 km/s). So during the quasistationary stage the condensed particles are localized mainly in the restricted spatial domain in
the vicinity of the capillary (up to 30-40 mm in length), do not reaching the front of the jet, and slowly fill the volume bounded by the contact surface during the relaxation stage.

![Image](https://via.placeholder.com/150)

**Figure 4.** Examples of time dependences of the optical thickness in the paraxial zone of a plasma jet at various distances z from the capillary outlet and at different discharge power densities q obtained at a wavelength $\lambda = 632$ nm: (1) $q=12.5$ kW/mm$^2$, $z=2$ mm; (2) $q=2$ kW/mm$^2$, $z=7$ mm.

The most intriguing moment is the sign-variable behavior of the optical thickness observed at the radiation wavelength of helium-neon laser $\lambda=632$ nm. As was found, the strange behavior of the optical thickness is connected with its nonmonotonic behavior in the spectral interval $\Delta\lambda=620-640$ nm characterized by an extremum at a wavelength $\lambda=628$ nm, in the vicinity of which the amplification of the probing radiation is observed (figure 5). The amplitude, width and position of the amplification peak are not strictly fixed on the wavelength scale and depend on many factors. In particular, these parameters can vary noticeably along the jet axis and radius, and also depend on the specific parameters of the discharge pulse. It seems that resonant phenomena associated with particle sizes can be considered as possible mechanisms responsible for the observed features, including the amplification of the probing electromagnetic wave. One of the possible mechanisms can be a plasmon resonance excited in the bulk or on the surface of small particles when interacting with an electromagnetic wave [14–16]. The study of this interesting problem will be the subject of future research.

Some of the above mentioned features, namely: the dependence of the optical thickness on the specific discharge parameters and on the spatial position of the probed region, - are also observed in other spectral ranges. These effects can be clearly seen on the graph shown in figure 6, where the values of the optical thickness in the paraxial zone of the plasma jet measured at fixed wavelengths for different distances from the capillary outlet and for different values of the capillary diameter (and, respectively, the discharge power density) are plotted. It can be seen that the optical thickness varies significantly with the distance from the capillary outlet and depends on the discharge power density. Moreover, the range of its dispersion at fixed wavelengths reaches the order of magnitude, which may be caused by inconstancy of the condensed particles parameters (concentration and average size) during their drift downstream. At the same time, the variability of the refraction coefficient, in particular, its sharp decrease for particles smaller than 20 nm [10], can be an equally important factor responsible for the observed dispersion. These factors lead to the fact that the dependences of the optical thickness on the wavelength of probing radiation, plotted for fixed discharge parameters and various parts of the jet, differ markedly from each other (figure 6). The course of these dependences, in general, becomes nonmonotonic and differs in general case from the Rayleigh approximation $\tau \sim 1/\lambda$ [12].
Figure 5. Dependences of the optical thickness in the paraxial zone of a plasma jet in the wavelength range $\lambda=620$-650 nm at different distances $z$ from the capillary outlet for the moment of time $t=4$ ms after the discharge ignition: (1) $z=2.5$ mm, (2) $z=5$ mm, diameter of capillary - $d=1$ mm.

Figure 6. Results of measuring the optical thickness in the paraxial zone of the plasma jet at various distances from the capillary outlet $z$ and for different diameters $d$ of the capillary, plotted for fixed wavelengths of probing source (449 nm, 536.5 nm, 636.5 nm, 726.5 nm). The data are obtained at the fixed moment $t=4$ ms after the discharge ignition.

4. Estimation of the condensed particles parameters

So, numerous experimentally observed features, namely: long recovery times of optical properties of the investigated region, which are more than an order of magnitude greater than the duration of the discharge pulse, sign-variable behavior of optical thickness in a number of cases, its strong inhomogeneity and nonstationarity, and also its dependence on the specific discharge parameters, allows us to conclude that the main contribution to the optical properties of erosion plasma give the processes involving condensed particles. The bremsstrahlung contribution from the high-temperature core of a plasma jet is negligible in this spectral range. The last conclusion is confirmed by the results of space-time spectroscopy made for erosion discharge plasma in [4]. According to the measurements of the electron density and temperature, the plasma in the paraxial zone of the initial section of the jet is strongly ionized: $n_e \approx [H^+] \approx (1-2) \times 10^{17}$ cm$^{-3} \gg n_i$, $T_e \approx 1.5$-2 eV, - and its ionization composition
determines hydrogen: \( n_i = [H^+] = [H] \), \( \alpha_i = 2n_i/n_{ei} \approx 1 \). According to [17,18], the absorption coefficient \( k_s \), connected with continuous emission coefficient by Kirchhoff’s law, is determined by equation

\[
k_s \approx n_i f(v,T_e) + n_e f(v,T_e)
\]

The first term in this equation takes into account free-free electron transitions in the ion field (bremsstrahlung) and free-bound transitions (photorecombination \( H^+ + e^{-} \rightarrow H + \nu \)), and the second one — deceleration of electrons in the field of atoms \( H \). According to estimates [17], the first term is dominant, and the absorption coefficient can be represented by the dependence [18] \( k_0 = 6.36 \cdot 10^{-47} \frac{2^2 e^2 n_i^2}{2 \hbar v_0} \frac{1}{\lambda^3} \). Estimates show that absorption coefficient in the paraxial zone \( (n_e=2 \cdot 10^{17} \text{ cm}^{-3}, T_e \approx 2 \text{ eV}) \) is \( k_0 \approx 10^{-2} \text{ cm}^{-1} \) for the wavelength \( \lambda = 525 \text{ nm} \). So, the bremsstrahlung from the paraxial zone of the jet is optically thin \( (\tau = k_0 A x \approx 2 \cdot 10^{-5}) \) and does not influence noticeably on the absorption properties of plasma.

One can use the dependence \( k_s = \sigma_0 N_0 \approx (\pi d_D^3/4) N_0 \) to estimate the concentration of the condensed particles \( N_0 \) if their sizes \( d_0 \) are known. To estimate the last parameter one can use the results of the analysis of the growth kinetics of small particles [19]. We believe that the main source of condensed particles (clusters) is carbon atoms, and the growth of clusters is determined by the processes of attachment in binary collisions. In our conditions, by virtue of the fulfillment of the criterion \( n_c^{1/3} \lambda_c \gg 1 \) \( (n_c, \lambda_c = 1/n_a \sigma_c \) – the concentration and the mean free path of carbon atoms, \( \sigma_c \approx 3 \cdot 10^{15} \text{ cm}^{-2} \) — scattering cross section of carbon atoms on the atoms of a buffer gas (hydrogen)), the kinetic regime of cluster growth is realized in which this process is characterized by a parameter [19]

\[
G = k_0/K_n a
\]

where \( k_0 = \sqrt{\frac{n_c f_e}{m_c} \frac{1}{\lambda}} - \) reduced rate constant of collision of atom with cluster; \( K \approx 10^{-42} \text{ cm}^6/\text{s} \) — triple rate constant of the formation of condensation nuclei; \( N_0 \) — concentration of the buffer gas atoms; \( r_W \approx 0.2 \text{ nm} \) — Wigner-Seitz radius for graphite. Taking into account \( T = 4000 \text{ K} \) and \( p = 1 \text{ bar} \) in the spatial domain of clusters formation, and also a stoichiometric gas composition \( C: H: O \approx 5: 8: 2 \), we obtain the values of the reduced collision rate constant \( k_0 \approx 2 \cdot 10^{-10} \text{ cm}^3/\text{s} \) and of the parameter \( G \approx 10^{-4} \text{ cm}^3/\text{s} \). In this case, the parameters describing the transformation of atomic vapor into a gas of clusters take the following values [19]

\[
n_{mid} = 1.2 G^{3/4} \approx 1200 - 6700, \quad \tau_0 = 3.2 G^{1/4} (k_0 n_c) \approx 0.2 - 0.4 \text{ \mu s},
\]

where \( n_{mid} \) — the average number of atoms in a cluster, \( \tau_0 \) — the time necessary for this conversion.

Thus, the average cluster size will be \( d_0 \approx n_{mid}^{1/3} r_W \approx 2 - 4 \text{ nm} \). Taking into account the results of measuring the optical thickness (figure 3), the concentration of condensed particles in the peripheral zone of the jet will be \( N_0 = k_0/\sigma_0 \approx (1.5) \cdot 10^{15} \text{ cm}^3 \), and their volume fraction — \( f_v = N_0 V_p/(0.1 - 3) \cdot 10^{-6} \) (here \( V_p \approx n_{mid} r_W \) — the volume of one cluster). In this case, the time required for the formation of one cluster is more than 4 orders of magnitude shorter than the duration of the discharge pulse \( (T = 9 \text{ ms}) \), that provides the conditions for conversion a significant portion of the atomic vapor localized at the jet’ periphery into the gas of clusters.

The estimates show that the interaction of the probe radiation with the erosion plasma containing condensed particles corresponds with good accuracy to the Rayleigh approximation \( (d_0 \ll \lambda) \), according to which the attenuation of probing radiation is determined entirely by its absorption [12]. The ratio of the scattered to the absorbed radiation is proportional to \( (d_0/2\lambda)^2 \) and for \( d_0 \approx 10 \text{ nm} \) is less than \( 5 \cdot 10^{-2}\% \), which allows us to neglect the scattering in optical thickness measurements.

5. Study of the condensed phase structure by scanning electron microscopy

The results of direct measurements made on a scanning electron microscope (SEM) lead to higher dimensions of the condensed particles if to compare with estimates based on the results of optical
thickness measurements. Preparation of samples intended for SEM study was carried out by depositing the condensed particles on pre-prepared substrates (glass, silicon, copper, aluminum) placed perpendicular to the axis of the jet at a distance of 35-40 mm from the capillary outlet.

A complex structural organization of the condensed phase consisting of fractions (particles, aggregates and compounds) of various sizes and shapes was revealed (figure 7-9). The size of the smallest fraction (particles) that can be reliably measured by SEM is in the range of 6-30 nm (figure 7). The shape of the particles is close to spherical. The particles are packed densely and form several layers on the substrate. In a number of cases the continuous layers can be formed as a result of the fusion of neighboring particles, whose bumpy surface reflects the specific shape and size of the constituent particles (figure 8). Films with a thickness of less than 1 nm are also observed, which, apparently, are formed as a result of the fusion of fine particles (zones marked as "Films" in figure 8). These fine particles form a larger fraction with characteristic sizes of 6-30 nm. The particle size of this fraction depends on the specific parameters of the capillary discharge. In particular, their dimensions decrease with increasing power density and, consequently, the plasma temperature (compare figure 7(a) and figure 7(b)), that consistent with the results of measuring the optical thickness of the plasma.

Figure 7. Microstructure of the surface of a condensed phase deposited on a silicon substrate by a plasma jet at a discharge current density (a) $I=80$ A/mm$^2$ and (b) $I=400$ A/mm$^2$.

Figure 8. Microstructure of the layer formed as a result of fusion of neighbouring particles. The substrate material is aluminum.
The next larger fraction, which characteristic size reaches 150-250 nm, is formed from the particles of the previous fraction (figure 9(a) and figure 9(b)). Particles of this fraction are also characterized by a predominantly spherical shape. In some cases, the particles of this fraction are aligned in chains and form fractal aggregates resembling snowflakes, or Liechtenstein figures, whose size reaches several micrometers (figure 9(c)). There are also larger compounds of submicron-micron sizes of irregular shape formed by fractions of different hierarchical levels.

![Figure 9](image)

**Figure 9.** Microstructure of the surface of the condensed phase. Substrate material: (a), (b) - aluminum, (c) - copper.

The variety of observed fractions, especially of submicron-micron sizes, is mostly the result of interaction and subsequent transformation of the initially deposited particles during the "aging" process, taking place under the normal conditions in later times after the jet exposure on the substrate. The formation of particles of submicron-micron sizes during the exposure of the substrate seems unlikely, even in the low-temperature peripheral zone of the jet (T=4000-6000 K). Apparently, the characteristic size of condensed particle during the discharge pulse is still closer to the estimates obtained on the basis of the optical thickness measurements, i.e. d_0~2-4 nm. The particles size of 20-30 nm observed by the SEM may represent the largest fraction, formed either in a "cold" zones of the jet or during the relaxation stage.
6. Conclusion

Thus, the absorbing properties in the optical wavelength range of the erosion plasma created by a capillary discharge are determined to a large extent by the parameters of the condensed particles formed in relatively cold discharge zones - in the near-wall layer inside the capillary and in the peripheral zone of the plasma jet. The estimation of the characteristic size of the condensed particles, based on the kinetics of their growth, gives the value \( d_D \approx 2-4 \text{ nm} \) that is in good quantitative agreement with the dimensions of the smallest fraction of the condensed phase observed on the SEM. The concentration and the volume fraction of the condensed particles in the peripheral zone of the plasma jet reaches respectively \( N_D \approx (1-5) \times 10^{13} \text{ cm}^{-3} \) and \( f_V \approx (0.1-3) \times 10^{-6} \). The time required for the formation of one particle is about \( \tau_D \approx (0.2-0.4) \mu \text{s} \) that more than 4 orders of magnitude shorter than the duration of the discharge pulse \( T=9 \text{ ms} \), that provides the conditions for converting a significant portion of the atomic vapor localized at the jet’ periphery into a gas of clusters.

The observed nonmonotonic course of plasma optical thickness in the visible spectral range, as well as its sign-variable behavior in the spectral range \( \Delta \lambda = 625-640 \text{ nm} \), indicate complex processes of the erosion plasma interaction with electromagnetic waves, which does not reduced only to absorption of radiation by condensed particles. It seems to us that resonant phenomena associated with the particle sizes can be considered as possible mechanisms responsible for the observed features, including amplification of electromagnetic waves in relatively narrow spectral intervals. As a possible candidate for the role of such a mechanism, one can consider plasmon resonance excited in the bulk or on the surface of small particles when interacting with electromagnetic radiation \([12,14-16]\). The study this issue, which is of unquestionable scientific and practical interest, will be the subject of future research.

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