About graphite evaporation dynamics caused by radiation in near zone of magnetoplasma compressor discharge

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Abstract. The results of processes above the surface of graphite samples which exposed with powerful vacuum ultraviolet (VUV) radiation experimental studies are presented. The characteristic radiation exposure time was 3...100 µs, the radiation energy in the vacuum region of the spectrum was 1...2 kJ. The main characteristics of the processes were recorded on direct, shadow photographs and interferograms. The temporal dynamics of the expansion of the plasma layer formed during evaporation of the flat graphite targets surface by VUV radiation, as well as the dynamics of buffer gas compression and shock wave motion are analyzed. It is shown that the temperature of the carbon plasma above the samples surface reached 1 eV. Research is relevant in the fields of space, plasma technologies, the development of the element base of microelectronics and fundamental studies of the powerful radiation interaction with matter.

1. Introduction

The phenomenon of light erosion is realized in a wide range of devices and technical applications. For example, light erosion (ablation) can occur when the surface of materials is treated with plasma [1], [2] and radiation [3], [4] flows, during the formation and modification of nano-structured relief on the surfaces of various construction materials [5], in ablative pulsed plasma thrusters and electric propulsion systems [6], in plasma dynamic sources of UV/VUV/EUV radiation [7], [8], etc. Of great interest is the impact of powerful radiation on the matter when a photons energy higher than the ionization potential of the samples atoms (i.e. radiation of the vacuum ultraviolet spectrum range). For many such devices, the plasma-forming substance is polymers, dielectrics, special heat-protective coatings, etc. These materials are ablated under the influence of radiation from the discharge, and the efficiency of such devices is largely determined by the ability to control the dynamics of the mass flow of the ablating material. At the same time, the determination of the characteristics of the light-erosion plasma and its spatial and temporal dynamics is important for studying the gas-dynamic "response" from the surface. This explains the interest in these studies.

2. Experimental setup

The study of the interaction of high-power fluxes of short-wave radiation of the UV and VUV spectral range with graphite samples was carried out on an experimental setup described in [9]. This setup was created on the basis of a plasodynamic discharge – the discharge of an erosion type magnetoplasma compressor 1, 2, 3 (Figure 1) [7, 9, 10], which was installed in a vacuum chamber 4. The source of radiation in such a discharge is a plasma focus, which is formed on the axis of symmetry near the central
electrode [11]. Such discharges are characterized by high spectral-brightness characteristics of radiation in the UV and VUV spectral regions and have an extended glow region [8, 11].

Plasmodynamic, radiative and electrical properties of this MPC have been presented in a number of articles and reviews [10 – 12]. These properties describe both the features of the discharge itself with a good efficiency of ≈ 70…90%, and radiation with high-performing spectral-brightness characteristics in the UV and VUV spectral regions with a light emission efficiency of ≈ 40…60% of the energy deposited into the plasma.

The experimental methods were similar to our previous works [9, 13]. The vacuum chamber was pumped out to a pressure of $p \leq 1$ Pa, then filled with background gas (in this series of experiments we used Ne). This procedure was repeated after each discharge, since erosion processes change the radiation spectrum of discharge. Capacitive storage 5 (a battery of low-inductance capacitors with a capacity of 18 $\mu$F, 25 kV) was switched with the MPC using a thyratron 6 (Pulsed Technology Ltd., Ryazan, Russia). Current waveforms were recorded with Pearson current monitor 110 (7) and Tektronix TDS 2024b oscilloscope.

Graphite bars (with dimensions of 30 mm×50 mm and a thickness of 10 mm) 8 were used as samples for the VUV exposure. They were installed with their long side along the discharge axis as shown in Figure 1. Thus, the nearest sample end to the MPC barrel received 2…2.5 times more energy than the far end. This made it possible, among other things, to register different modes of expansion of a vapor-plasma flow when moving from one end of the target to another. The pressure of background gas (neon) in the chamber was $p_0=5.32 \times 10^4$ Pa (a density was $\rho_0=0.9$ kg/m$^3$). The charging voltage of the capacitor was $U_0 = 20$ kV that corresponded to a stored electrical energy of 3.6 kJ.

![Figure 1](image.png)

**Figure 1.** 3D model (a) and photo (b) of experimental set up: 1 – central electrode, 2 – external electrode, 3 – ablative dielectric, 4 – vacuum chamber, 5 – capacitor, 6 – thyatron, 7 – current monitor, 8 – samples holders.

Optical laser diagnostics was used for visualization and quantitative study of a gas-dynamics response from the graphite samples under the VUV radiation. It included double-exposure holographic interferometry and the Toepler’s schlieren scheme in the bright field mode [9, 14 – 16].

The method of plasma flows laser diagnostics used in our research was described in [9]. The peculiarity of the technique used is that we get a hologram of a focused image [15] with visualization of large optical fields (in our case 150 mm) with a constant resolution (no more than 50 microns).

Note that the emission spectrum of the MPC discharge respect to time. At first, the main radiation energy is concentrated in the visible spectrum range. We assume that under the influence of this radiation, the surface of the samples is heated, and their diffuse evaporation also takes place. At about 5 $\mu$s after the discharge start, a plasma focus is formed, emitting in the VUV range (this moment should correspond to the maximum discharge current). Under the influence of VUV radiation, carbon vapor...
ionization occurs (ionization potential $I_C = 11.25$ eV, the buffer gas transmission boundary is determined by the ionization potential $I_{Ne} = 21.6$ eV). Photoionization of carbon vapor leads to the formation of a plasma layer above the surface of the samples. This plasma, expanding, creates a "plasma piston", above which there was a layer of buffer gas compressed by the impact and a shock wave.

3. Results discussion

Figure 2 shows interferograms of near-surface layers above a graphite sample obtained with different delays (6 and 8 $\mu$s) from the beginning of the discharge. The moment of the photo was determined by oscillograms (Figure 3), in which channel 1 is a photodiode signal that captures a pulse of probing laser radiation (the moment of receiving the interferogram), and channel 2 is a discharge current oscillogram (attenuated by 10).

![Figure 2](image1)

**Figure 2.** Graphite evaporation interferograms (a – at 6 $\mu$s, b – at 8 $\mu$s)

![Figure 3](image2)

**Figure 3.** Current oscillograms (a – at 6 $\mu$s, b – at 8 $\mu$s)

The analysis of the obtained interferograms (Figure 2) makes it possible to determine the parameters of both the shock wave and the shock-compressed layer and the plasma layer formed from the vapors of the sample material as a result of effective photoionization. The general principles of obtaining quantitative information from the phase inhomogeneities interferograms are described in the literature [15, 16]. The feature of the experimental scheme is that the length of the probing laser radiation optical
path in the "phase inhomogeneity" is constant, which greatly simplifies the processing of interferograms. The interpretation of interferograms in our experimental scheme is described in detail in [13].

The features of the shift of interference fringes over a graphite sample (Figure 2) are associated with plasma formation above the surface and expansion of the carbon plasma in the background gas (in neon). A detailed description of the characteristic areas of interferograms is given in [13]. The upper part of the interferograms is the undisturbed region corresponding to the background gas at the initial pressure \( p_0 \approx 5.3 \times 10^4 \) Pa. The next shift of the fringes to the right (jump) this is a sharp change in the density of the gas in the shock wave. Below is a layer of shock-compressed gas. Since the interference fringes in the shock-compressed gas are smooth, this indicates a slight change in its pressure in height. After that, the fringes turn to the left. The area from this turn to the sample surface is the plasma layer. The bending of the fringes in this region shows a change in the refractive index \((n-1)\) in the plasma layer and reflects the complex dependence of the thermodynamic parameters of the plasma on the height above the graphite sample.

At the time of the interferogram registration, the background gas occupies the volume from the contact boundary to the shock wave. At the initial moment, the background gas occupied the entire volume from the sample surface to the shock wave. Assuming that the contact boundary moves at speeds less than the local speed of sound, we assume the process isobaric.

From Figure 2a we determine that at 6 \( \mu s \) the compression ratio of Ne is approximately 1.5 times, and at 8 \( \mu s \) (Figure 2b) the compression ratio is approximately 1.4 times. The presence of interferograms makes it possible to refine the compression degree using the relationship of the fringes shift with the change in gas density (due to changes in the refractive index).

So, at the 6 \( \mu s \), the background gas is compressed by about 1.44 times, at 8 \( \mu s \), the compression ratio is approximately 1.35. Using the shock adiabat, knowing the ratio \( \rho_0/\rho_1 \), the pressure ratio \( p_1/p_0 \) can be determined as [16]:

\[
\frac{p_1}{p_0} = \left( \frac{\gamma + 1}{\gamma - 1} - \frac{\rho_0}{\rho_1} \right) \left( \frac{\gamma + 1}{\gamma - 1} - 1 \right)^{-1}
\]

Under the implemented conditions for a monatomic gas (with an adiabatic index of \( \gamma = 1.67 \)) for \( p_1/p_0 \approx 1.44 \), the absolute value of the pressure behind the shock wave front was \( p_1 \approx 9.9 \times 10^4 \) Pa.

Knowing the position of the shock wave front for two consecutive time moments, we determine its velocity \( V_{sw} \sim 700 \) m/s. At the same time, the speed of sound in neon is \( V_s \sim 455 \) m/s. Thus, the Mach number is approximately \( M \sim 1.5 \).

Under the assumption of local thermodynamic equilibrium, the change in the refractive index in the plasma (the shift of interference fringes in the plasma) and the plasma parameters have an unambiguous relationship [17]:

\[
\Delta n = \frac{L}{\lambda} \left[ 2\pi \sum x_N N_x - 4.49 \cdot 10^{-14} \alpha_e \right] n_0
\]

here \( N_x \) is the partial concentration of atoms or ions, \( \alpha_e \) is the ionization degree, \( n_0 \) - plasma concentration, \( \alpha_s \) is the dipolar polarizability of the atom or ion [18]. Thus, the maximum plasma temperature is about 10 kK (1 eV) inside the plasma layer.

4. Conclusion

Processing of the interferograms made it possible to determine the parameters of graphite plasma during evaporation of a samples by VUV radiation. A method of diagnostics and quantitative description of the parameters of plasmodynamic structures arising from the interaction of powerful broadband radiation on the surface of structural materials is proposed. Information about the processes is obtained as a result of a limited series of experiments (practically - a single one). As a result it is possible to determine both parameters of generated flows (pressure, density in shock-compressed layer, etc.) and thermodynamic parameters inside plasma. So, plasma temperature above graphite target surface (in approximation of local thermodynamic equilibrium) was about 10 kK.
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