LASER HEATING OF ITS EROSIONAL LOW-TEMPERATURE PLASMA IN THE PROCESS OF GASDYNAMIC MOTION

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A study is made of the gasdynamical and optical properties of erosional laser plasma jets in the presence and absence of laser radiation. It is shown that in processes of plasma formation during the action of laser radiation of moderate intensity ($q \approx 10^7$ W/cm^2) on absorbing materials,the heating of the disintegration products by the attacking laser radiation plays an important role. The temperature distribution is obtained along the plasma jet which forms during the laser attack counter to its propagation in a quartz tube confining the dispersion. The temperature maximum is found at the exit from the tube, is caused by the heating of the erosional laser plasma by the incident laser radiation in the process of its one-dimensional gasdynamical motion, and indicates the screening of the surface from the laser radiation. It is established that the screening is affected by the gasdynamical structure of the plasma jet and by the spacing of the plasma clusters corresponding to the regular pulses of laser radiation.

1. The theory of the phenomenon of heating of vapors by laser radiation during its attack on opaque materials is developed in [1, 2]. The experimental work of [3] carried out on this plan is well known. Experimental facts pointing to the heating of disintegration products by laser radiation and the screening of the surface from the laser radiation at moderate flux densities were discovered in [4-10]. In a report on the experimental study of the optical properties of an erosional low-temperature laser plasma in the surface region [11], results were obtained in qualitative agreement with the theory of heating of an erosional laser plasma of [1, 2]. The present report is devoted to a comparative study of the optical properties of an erosional laser plasma during its heating during the process of gasdynamical motion and without heating.

The design of the experimental instrument and the diagnostic apparatus is analogous to that described in [5, 6]. The studies were conducted with a neodymium-activated glass laser in the regular generation mode. The laser provided a radiation energy of ~150 J and produced relatively uniform pulses of radiation with a spacing of 3 μsec and a duration of 1 μsec each [11]. The duration of laser generation was 700 μsec.

The attack of the laser radiation of the plasma-forming material (brass wire) occurred under conditions of confinement of the dispersion of the plasma formed by a quartz tube projecting above the plasma-forming material. The system of attack counter to the forming plasma jet (from above) and perpendicular to it (from the side) which was chosen made it possible to conduct comparative studies of the plasma jets with and without the passage through them of the attacking laser radiation.

The length of the confining quartz tube (inner diameter ~2 mm) of ~3 mm above the surface of the brass wire was also chosen so as to ensure durability and retain the plane geometry of the dispersion of the disintegration products during the action of an individual radiation pulse. The diameter of the wire (~2 mm) was commensurate with the diameter of the focusing spot.

The focusing of the radiation was accomplished with a lens with a focal length of 100 mm to a spot with a diameter of 2.4 mm. The length of the cylindrical part of the focal caustic of the lens was ~10 mm. The flux density of the radiation was determined with allowance for the spacing and was ~10^7 W/cm^2. The

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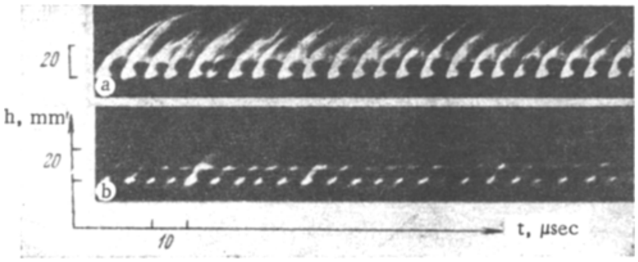

Fig. 1

TABLE 1

Nature of attack	v_1, km/sec	v_2, km/sec	v_3, km/sec	l, mm	p_1, atm	p_2, atm	d, mm
From above	5.5	1.3	4	6.5	26	1	2
From the side	4	1	2.3	6	22	1	2

plasma-forming material used was LS-59 brass. The studies were conducted at atmospheric pressure by spectroscopic and high-speed photographic methods.

The spectra of the plasma jets formed were recorded with ISP-30 and ISP-51 spectrographs (camera with F = 270 mm) along the jet. In measuring the absolute values of the brightness,the plasma spectrum was compared with a calibrated Si6-100 ribbon-filament lamp. The ratio between the emission times of the plasma ($\sim 10^{-4}$ sec) and the standard lamp (~ 10 sec) in the photographic recording was chosen in such a way that the sensitivity of the film was the same for both exposures. The emissivity of tungsten was taken from [12] and the brightness of a black body was taken from [13].

2. The attack of laser radiation on absorbing materials under conditions of localization and confinement of the dispersion of the erosional plasma formed leads to the formation of supersonic underexpanded plasma jets with a definite gasdynamical structure [14]. The gasdynamical structure of the plasma jets is determined by the ratio of pressures in the quartz tube and in the surrounding medium. A mode of outflow with the formation of a stationary shock wave in the plasma jet was studied in the present work.

The formation of successive moving shock waves is a characteristic of the gasdynamic dispersion of an erosional laser plasma formed during the attack of laser radiation in a regular mode of generation on absorbing materials [6]. The formation of moving shock waves also occurs during laser attack under conditions of confinement and the directional dispersion of the forming erosional plasma because of the interaction of individual plasma clusters with the surrounding medium which is the vapor of the material undergoing laser attack. High-speed longitudinal photoscans of plasma jets formed during laser attack counter to the plasma jet (a) and perpendicular to it (b) are presented in Fig. 1, where h is length and t is time.

The moving shock waves are seen on the longitudinal photoscans beyond the stationary shock wave upon entry into the plasma produced by the preceding radiation pulses (Fig. 1). They have a higher velocity than the plasma clusters whose velocity abruptly decreases at the stationary shock wave (Table 1). The following notation is adopted in the Table 1: v_1 is the velocity of the moving shock wave before the stationary shock wave, v_2 is the velocity of the plasma cluster beyond the stationary shock wave, v_3 is the velocity of the moving shock wave beyond the stationary shock wave, l is the length of the stationary shock wave, p_1 is the pressure at the nozzle cut, p_2 is the pressure of the surrounding atmosphere, and d is the nozzle diameter.

During the attack of laser radiation directed perpendicularly to the propagation of the forming disintegration products (from the side),the plasma emission is much weaker (see Fig. 1b) in comparison with the case of attack counter to the moving disintegration products (from above) (Fig. 1a). The stationary shock wave is less strongly expressed in this case and its distance from the surface is less (see Table 1).

The moving shock waves are more intense during laser attack from above (Fig. 1a), which is connected with the partial absorption of the laser radiation. Periodically repeating vertical bands of increased intensity are observed on the longitudinal photoscans which are caused by heating of the plasma formed by the preceeding radiation pulses during the passage of the succeeding pulses. The nature of the emission of individual spectral lines obtained by photoelectric recording also indicates the absorption of laser radiation.

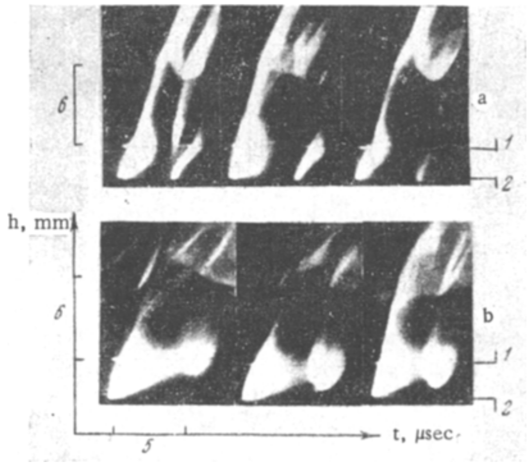

Fig. 2

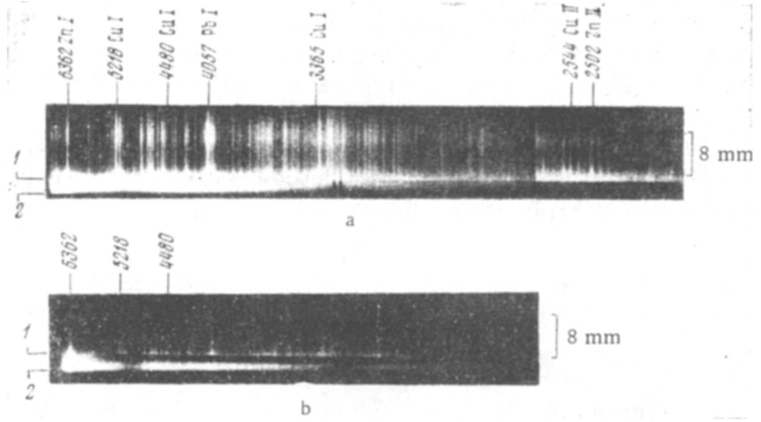

Fig. 3

The emission of the individual spectral lines is sensitive to a change in the flux density of the laser radiation. As seen from synchronous oscillograms, the emission of the spectral lines occurs with pulsations connected not only with the regular structure of the laser radiation, but also with the change in the amplitude of individual pulses of radiation because of its absorption by the plasma.

The attenuation of the laser radiation can be affected by the gasdynamical structure of the plasma jet, particularly by the stationary shock wave which forms [7]. The degree of attenuation depends on the spacing of the forming plasma clusters and the conditions of outflow (the confinement of the discharge and the length of the confining quartz tube). If the stationary shock waves from the preceding pulses still exist in the plasma clusters by the start of the following laser radiation pulses, then a burst of absorption occurs at the shock wave because of the partial absorption of the laser radiation of the following pulse (Fig. 2a). In Fig. 2 the number 1 denotes the cut of the quartz tube and 2 denotes the surface of the wire in the quartz tube. If the length of the confining quartz tube is such that the forming plasma cannot emerge from the tube by the start of the following pulse, "blanking" of the radiation may occur (Fig. 2b). The absorption of the laser radiation by the forming plasma may lead to total screening of the surface and separation of the plasma jet from it [5].

To obtain quantitative data, a mode of outflow was selected and studied in which the confining quartz tube had a length (~3 mm) which the forming plasma traversed by the moment of the drop in intensity of the individual laser radiation pulse. Since the process of plasma outflow has a quasistationary nature because of the identical nature of the individual attacking pulses of laser radiation, the total gasdynamical flow pattern reflects the flow in an individual pulse. On the basis of the study of the gasdynamical structure of the plasma jets, their parameters, which are given in Table 1, were determined from the equations presented in [14].

3. A comparative analysis of the longitudinal emission spectra of the plasma jets with and without

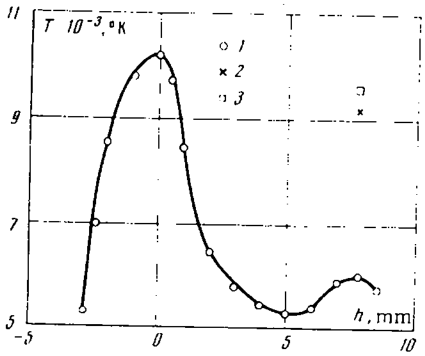

Fig. 4

their heating makes it possible to establish the difference in the nature of their emission. In the case of attack from the side (without heating), the spectrum beyond the cut of the tube is very meager, especially in the ultraviolet region (in Fig. 3b the number 1 is the cut of the quartz tube and 2 is the surface of the wire). It represents weak continuous radiation against the background of which the self-reversed lines are seen. Sometimes one or two extremely weak lines of ions are seen. During attack from above (with heating), an intense spectrum is seen (Fig. 3a) in which a brightly expressed jump in emission intensity corresponding to the stationary shock wave is observed. The gasdynamical structure which appears on the longitudinal integral spectra reflects a real process since the plasma jets are quasistationary in time. Many lines are self-reversed to a height of 2-3 mm, especially in the spectral region of 2400-2700 Å. Some of the lines are also self-reversed at the cut of the quartz tube and at the stationary shock wave and are seen in radiation only ahead of the stationary shock wave and behind it.

Measurements of the dependence of the intensities of the continuous radiation and of the individual spectral lines along the jet showed that in the case of attack from above, the intensity reaches a maximum at the exit from the quartz tube (at a distance of ~3 mm from the surface). The intensity then falls and abruptly increases at the stationary shock wave, but does not reach the intensity at the exit. With attack from the side, a dip is observed in the intensities of the continuous spectrum and the spectral lines upon approach to the cut of the quartz tube. This is connected with the fact that many drops settle on the wall of the tube near its cut and a fine film is formed, probably because of the condensation of vapors of the brass on the wall. The intensity drops sharply beyond the exit from the quartz tube and increases slightly at the stationary shock wave.

The continuous radiation and the spectral lines were used to determine the plasma parameters. The temperature measurement was made by comparing the brightness of the continuous radiation of the plasma studied (λ = 4550 Å) with the brightness of a standard source. The temperature dependence along the plasma jet in the case of attack from above is presented in Fig. 4 (0 on the h axis corresponds to the cut of the quartz tube and 1 is the brightness temperature). The temperature reaches a maximum at the exit from the quartz tube. The increase in temperature is connected with the heating of the plasma in the process of its motion in the tube under conditions of confinement of the dispersion. Then the temperature drops and at the stationary shock wave it almost reaches the temperature of the plasma upon exit from the tube (Fig. 4-2, -3), which is caused by the heating of the plasma in the region of the stationary shock wave during the passage of each successive pulse.

Measurement of the absorptivity of the plasma using a system described in [11] showed that in the quartz tube it is close to unity. This makes it possible to compute the plasma temperature in a given region from the measured brightness temperature. With attack from the side, the temperature could be measured only in the quartz tube (at the base of the jet). It proved to be 6000° K. In the region near the surface the temperature of the plasma jet formed during laser attack from the side was somewhat higher (~6000° K) than the temperature of the jet which forms during attack from above ~5300° K). This is connected with lateral heating of the plasma in the irradiation spot.

The Cu I 4480 Å line was taken for the measurement of the electron concentration, for which the constant of the quadratic Stark effect was adopted from [15]. As measurements with spatial resolution showed, this line alone does not display marked self-absorption in the region of the stationary shock wave and it can be used to determine the electron concentration. The electron concentration at the stationary shock wave was $1.3 \cdot 10^{17}$ cm^{-3}.

The plasma temperature at the stationary shock wave, equal to 9600° K (Fig. 4, 3), was obtained on the basis of the calculated plasma composition for a pressure of 1 atm and the measured electron concentration ($n_e = 1.3 \cdot 10^{17}$ cm^{-3}). The plasma temperature can also be determined from the experimentally measured absolute value of the coefficient of continuous radiation (λ = 4450 Å), based on the calculated data on the emissivity of the plasma. It was 9200° K (Fig. 4-2).

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