Study of plasma and particles flows from shock-loaded metal target with lateral lighting by argon explosive lamp

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Abstract. Experimental estimates of the process of the ejection of particles and the formation of plasma during the shock wave exits on the free surface of the cooper sample studied were carried out. The radiation intensity was recorded by a three-channel pulsed pyrometer in an experimental assembly with lateral observation. When the impactor speed was about 5 km/s, a stream of particles and plasma flew from the target surface, the front speed of which reached 12.5 km/s.

1. Introduction
The emergence of a strong shock wave on the surface of various substances, especially metals, attracts experimenters and theorists for a rather long period of time [1]. It is shown that, when a shock wave arrives at the free boundary of a material, a flow of particles of small dispersion and cumulative jets is formed [1, 2]. This phenomenon can be caused by various defects inside the metal and on its surface, such as surface roughness and the presence of microscopic grooves on it and defects inside the material-grain boundaries, possible foreign inclusions or unfilled volumes.

In the literature there are various estimates of the speed of movement of microparticles. In the main a registered speed of particles was no more than 1.5 times larger than free surface velocity. When using piezoelectric sensors, emissions were recorded with speed exceeding 2.5 times [3]. In [2], it was found that metal foils with a thickness of 0.05 to 0.5 mm are punched by high-speed particles with a size of 10–100 µm. Particularly important is the problem of the formation of streams of microparticles during gas-dynamic plasma compression in relation to inertial thermonuclear fusion [4]. In the works [5–8] various methods of research of this process are presented, it is shown that the flow consists of particles with a wide discreteness spectrum: from single ions to clusters. This description is based on the use of pyrometric diagnostic methods with lateral observation to study plasma flows and metal particles formed on the surface of shock-compressed samples. The technique uses the time-of-flight method of measurement on a fixed base. This technique was successfully used by the authors in estimating the energy loss of carbon ions in a nonideal argon plasma in a series of explosive experiments at an accelerator in the Helmholtzzentrum für Schwerionenforschung GmbH (GSI–Darmstadt) [9].

Earlier in [8], using spectroscopy, we showed that when a strong shock wave reaches the free surface of the copper membrane, a plasma flow of the target material is formed, which moves at a
speed of 10 km/s, which is approximately 2 times higher than the target velocity. In this work, a multichannel pyrometer designed and manufactured at the IPCP RAS is used to quantitatively measure the intensity of radiation. The optical system of division of light into 3 channels is applied in a pyrometer with a fiber entrance. Each channel has an interference filter with a bandwidth of 10–40 nm. Flint pin diodes, broadband low-noise photocurrent amplifiers with a 0–100 MHz band were used. The pyrometer allows measuring brightness temperatures from 1600 K and above with a time resolution of \( \approx 5 \) ns.

2. Experimental technique

To find the absolute values of the radiation intensity, the optical system of the measuring channel was calibrated. A calibrated SIRSh-8.5-200-1 incandescent tungsten filament lamp was used as a reference radiation source. The temperature of the emitting tungsten band was determined using an EOP-66 optical pyrometer, at a wavelength of 0.65 ± 0.01 \( \mu \text{m} \), with an accuracy of 6 K. The measured temperature of the lamp was used to determine the true temperature of the tungsten tape, which was later used to determine the degree of blackness of tungsten \( \varepsilon(T, \lambda) \) in the calculations of the brightness temperature of the measured source. The transmission of optical windows made of quartz, glass and Plexiglas was taken into account according to Fresnel formulas for normal incidence, taking into account the dependence of the refractive index on the wavelength. The operating point of the lamp with the thermodynamic temperature of tungsten was 2700 K. Absolute intensities by channels were determined using calibration according to the method described in [10]. The calculation of the temperature recorded in the experiments was carried out as in [11].

The experimental assembly is shown in figure 1. During operation, an explosive generator accelerates by explosion products a flat steel drummer 1 mm thick to a mass speed of \( \approx 5 \) km/s. The impactor hits the copper target with a diameter of 40 mm and a thickness of \( \approx 0.5 \) mm below. The target is fixed in the base. When a shock wave reached the free surface of the membrane in the chamber volume, plasma and particles ejected from its surface into the helium atmosphere or into vacuum. In the chamber filled with helium, a shock wave will be generated, moving at a speed of \( \approx 6.8 \) km/s. Helium was chosen to fill the assembly due to its high ionization potential. Up to a shock velocity of \( \approx 8.5 \) km/s, the degree of ionization of helium is low and the electron concentration does not exceed \( 10^{16} \) cm\(^{-3} \), while helium remains optically transparent. It was connected to the camera through the glass and the tube.

The chamber volume was evacuated and, if necessary, filled with helium through the nozzle. Coaxially with the argon illumination channel there is a steel capillary into which the optical fiber is inserted. The other end of the fiber connects directly to the pyrometer.

Pulsed argon illumination provides luminescence in a wide spectral range with radiation close to that of a black body with a temperature of 18 000 K (L direction). The luminescence remains almost constant in intensity throughout the entire time of passage of the shock wave along the length of the volume filled with argon. In this case, the shock wave passed through a tube with a diameter of 20 mm and a length of 120 mm, which provided illumination for \( \approx 15 \) \( \mu \text{s} \). This time is much longer than the process being studied.

The shock wave in the Cu target propagated in the U direction at a mass velocity of 2.45 km/s at a pressure of 1.63 Mbar. After the shock wave reached the surface, the plasma and particles scattered into a cylindrical volume, evacuated to a forevacuum \( \approx 0.001 \) bar. At a distance of \( d = 20 \) mm, perpendicular to the flow, a steel capillary with a light guide recessed into it by 7 mm was coaxially positioned and a tube through which radiation of an argon flash with an internal diameter of 6 mm was fed. The tubes were pushed into the assembly and the gap between the ends was 10–12 mm. The cone of field of view of the fiber was a diameter of not more than 3 mm. Perturbations from the edges of the assembly to the region along which the probing light and the fiber axis passed did not reach.
The experiments were carried out on the same assemblies with and without lighting. In this case, one can observe both the absorption of plasma and particles, and their self-luminescence. The results of several experiments are shown in figure 2.

In figure 2, until the time a, the flash light passes through the optical path unimpeded (the flash light corresponds to a temperature of 18 000 K). At the time a, the plasma enters the measurement gap, which is transparent to the illuminating radiation and does not affect it up to the interval indicated in the figure with the shaded area. The plasma expansion velocity is about 12.5 km/s and the self-glow temperature is \( \approx 2600 \) K. In the range of speeds 9.9–8.5 km/s, the illumination of the backlight lamp begins to overlap with a layer of opaque particles. Starting from the time b, the illumination glow completely overlaps with particles and only the own emission of particles with a temperature of \( \approx 4000 \) K is observed.

Experiments confirm the propagation of a plasma stream arising when a shock wave emerges on the target surface and a stream of particles. Plasma velocity exceeds particle flow rate. The emission of particles from the surface of metals at the velocity of dispersion of the main mass of the target material 5 km/s was accompanied by the formation of particles of different sizes, including the plasma of the target metal (copper), the line emission spectrum of which was previously observed in experiments on special recording of spectra [7, 8].

The velocity of movement of the main mass of particles was determined by the base method from the known distance from the target to the transparent barrier and from the time of the plasma glow change. It was experimentally shown that at least two particle flows fly from the surface: the first is a plasma, whose speed is about 12.5 km/s, and light particles, the speed of which is from 9.9 to 8.5 km/s. Estimates of the ejection velocities of particles from a metal surface when a strong shock wave hits it, made in [1, 2] show that the particle front exceeds the target velocity by 1.5–1.6 times. It is possible that we are talking about a stream of larger particles, which was registered by the available diagnostic methods. In this paper, the flow of ejected particles and plasma were registered by the pyrometric method with lateral observation, which is consistent with the experiments using the spectrometric registration method [8], and
3. Conclusions
As a result of the study of the plasma and fine particles emission from the target after the shock wave reaches the surface, the parameters of the intensity of the radiation emitted were obtained. We used the method of lateral observation with a pulsed stationary argon illumination and recording information using a pyrometer. Analysis of the experimental data shows that, under the experimental conditions, the plasma flow front moves at a speed of approximately 12.5 km/s. Further, in this flow, fine particles are observed that smoothly overlap the argon illumination, while the flow velocity is less than 9.9 km/s. The temperatures of plasma flow and particle flux were recorded. Obviously, the total flux will have a complex structure of the distribution of particles by radiation intensity, size and speed. In this case, the pyrometric method of research is promising, which will allow a more in-depth study of the problem of ejection of particles from the target surface when a shock wave arrives at it.

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