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IMMOBILE SHOCK WAVE PRODUCED UPON STATIONARY EVAPORATION OF METAL BY LASER RADIATION

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We have investigated the dynamics of spreading of metal vapor produced by surface heating of a metal target by powerful laser radiation. The laser-pulse duration was long compared with the characteristic settling time of vapor motion, so that the observed picture of the motion assumed a stationary character. We observed here for the first time an immobile (relative to the target) shock wave (SW), on the front of which supersonic vapor flow was transformed into subsonic flow[1].

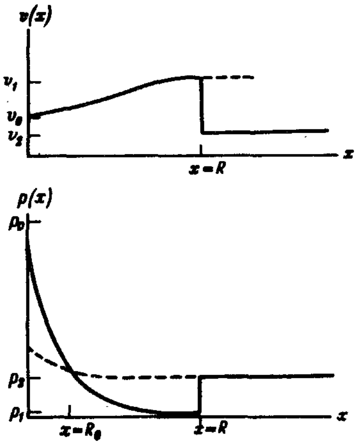

Fig. 1. Qualitative picture showing the change of the vapor velocity v and pressure p along the x axis (solid curves). The x axis is perpendicular to the target surface. The laser beam propagates in the negative x direction. The point x = R denotes the diameter of the immobile SW. The point x = 0 corresponds to the target plane, on which the initial conditions of the motion v_0, ρ_0, p_0) are specified. The indices 1 and 2 pertain to the values ahead of and behind the SW front.

The supersonic flow is produced in the region between the target and the SW front (the region $x < R$ in Fig. 1) if the vapor pressure p_0 at the target is much larger than the external gas pressure p_∞. This is accompanied by escape of matter from the target, and the vapor velocity $v(x)$ in the interval $0 < x < R$ increases from its initial value v_0 like [1]

$$v(x) = v_0\sqrt{1 + \frac{2}{\gamma - 1} M_0^{-2} \left(1 - \frac{c^2(x)}{c_0^2}\right)}, \tag{1}$$

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[1] A similar gasdynamic picture is observed in supersonic escape of gas from a nozzle in the underexpansion regime. The authors are grateful to P. I. Ulyakov and L. Ya. Min'ko for calling their attention to this analogy.

where $\gamma = 5/3$ is the Poisson adiabatic exponent, $M_0 = v_0/c_0 \approx 1$ is the Mach number at $x = 0$, and $c(x) = \sqrt{\gamma kT(x)/m}$ is the speed of sound at the point x and decreases rapidly with the temperature $T(x)$ as x increases. The vapor pressure $p(x)$ also decreases, and when x is large enough it becomes smaller than p (see Fig. 1). A pressure jump is produced and is compensated by the SW at the point $x = R$. At this point the SW is immobile relative to the target, provided the velocity of the impinging gas $v(x)$ corresponds to the pressure jump on the target [1]:

$$v_1^2 = \frac{\gamma + 1}{2\rho_1} p_2 \left[1 + \frac{\gamma - 1}{\gamma + 1} \frac{p_1}{p_2}\right]; \quad p_1 = p(R), \quad \rho_1 = \rho(R), \quad v_1 = v(R). \tag{2}$$

It is clear from Fig. 1 that the SW is formed on the section $\Delta x = R - R_0$. At the point $x = R_0$, where it is a small disturbance, its velocity relative to the target is maximal and equals

$$V(R_0) = v(R_0) - c(R_0). \tag{3}$$

When $x > R_0$, this velocity decreases and vanishes at the point $x = R$.

The experiments were performed on bismuth placed in a helium atmosphere. The helium pressure ranged from 0.01 to 3 atm. The average intensity per pulse of laser radiation incident on the target was constant in all the measurements and amounted to $I = 0.7 \times 10^7$ W/cm^2. This corresponded to a laser (neodymium glass, $\lambda = 1.06$ μ) emission energy $E = 2.3$ kJ, an irradiated spot area $S = 0.4$ cm^2 (diameter $d = 0.7$ cm), and a pulse duration at the half-intensity level $\tau = 0.8$ msec. The background of the "spike" modulation on the radiation-

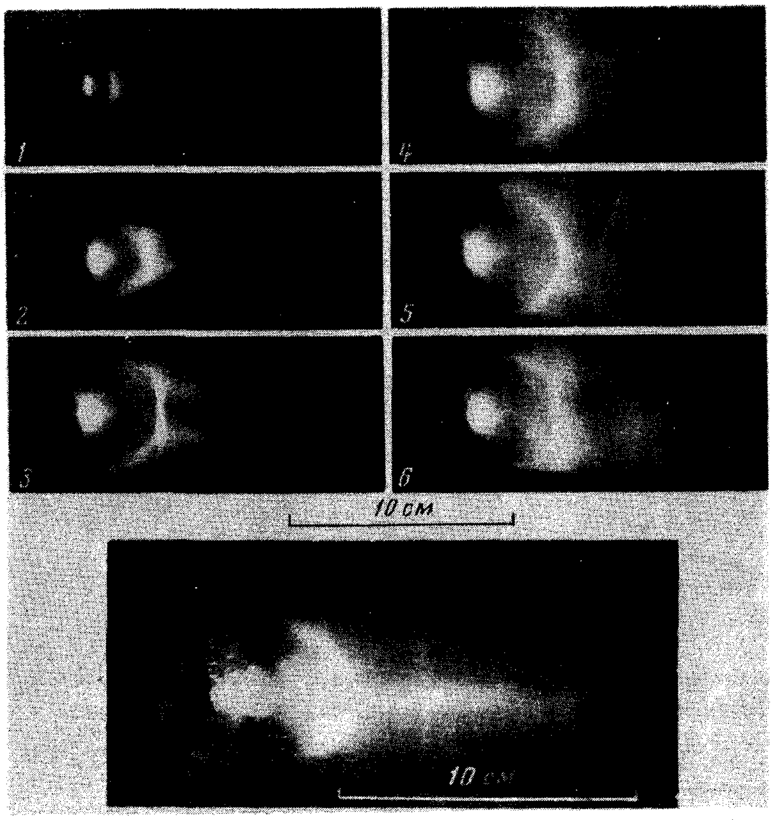

Fig. 2. Time scan of the motion of bismuth vapor in a helium atmosphere at a pressure $p_\infty = 0.25$ atm (frame by frame photography, side view). The time interval between the shown frames is 64 μsec. The laser beam travels from right to left. The lower photograph shows a front and side photograph of the process, taken with an exposure ∿ 1 sec (the small sphere between the target and the SW is due to parasitic reflections of the light from the walls of the cylindrical glass chamber).

pulse oscillogram did not exceed 30% of the pulse envelope. The cylindrical part of the caustic of the focusing lens (f = 100 cm) was approximately 10 cm.

The expansion of the metal vapor was investigated by high-speed photography of the vapor glow. Figure 2 shows by way of an example the photographs obtained at $p_\infty = 0.25$ atm, and illustrates the glow of the SW front. To the left of the SW is a region of stationary adiabatic expansion of the vapor. Glow of the vapor is seen near the target. On the right is the region of constant vapor flow (see Fig. 1).

The shock wave has the shape of a sphere tangent to the target. Photography at various angles shows that the surface of the sphere is transparent. Only its contour is seen, since the optical thickness is maximal along the contour. This SW shape corresponds to the following equation for the law of conservation of the material flow:

$$\rho_o v_o S_o = \rho v S \,, \tag{4}$$

where $S_0/S = d^2/4x^2$ (in the notation of Fig. 1).

Figure 2 shows the transient process of SW formation, the increase of its dimensions (frames 1 - 3) and the stationary part of the process (frames 4 - 6), when the SW dimension remains practically constant (a slight decrease of R with time is noted). The time interval corresponding to the stationary section 0.5 msec lies near the maximum of the time variation of the radiation-pulse intensity, where the intensity changes slowly.

A jet develops behind the SW front (Fig. 2), provided the particle mean free path is small compared with the transverse jet dimension. The jet velocity v_2 was determined from the displacement of its front. At $p_\infty \leq 0.25$ atm it turned out to be constant (within 10%) at 470 m/sec. The front of the jet is a tangential discontinuity separating the regions of motion of the helium and the bismuth vapor. The pressure on the tangential discontinuity is continuous, and therefore $p_2 = p_\infty$.[2)]

Further, it is possible to estimate the velocity v_1 from the experimental data. Since $v_2 = 470$ m/sec when $p_\infty \leq 0.25$ atm and R > 4 cm, while the maximum velocity jump at the SW is $v_1/v_2 = 4$ when $\gamma = 5/3$ [1], we get $v_1 \leq 1880$ m/sec at the indicated values of p_∞ and R. On the other hand, the rate of increase of the SW diameter, measured in the region of its production, $R_0 = 2.8$ cm, equals V = 1750 m/sec at $p_\infty = 0.01$ atm. Thus, in accordance with (3), the velocity v_1 lies in the interval 1750 m/sec < v_1 < 1880 m/sec at $p_\infty \leq 0.35$ atm and $R \geq 4$ cm. It follows therefore, in particular, that $v_1/v_2 > 3.7$ and therefore the observed SW can be regarded as strong.

The last result enables us to find the connection between the SW dimension and the helium pressure p_∞. Neglecting in (2) the term $(\gamma - 1)p_1/(\gamma + 1)p_2 \ll 1$, and combining the

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[2)] It should be noted that Fig. 2 shows an increase of the gas-jet glow with time along the laser beam, owing to the absorption of light in the jet. In the photograph at the bottom of Fig. 2, which shows the integral picture of the motion, the dimensions of the regions with increased brightness correspond to the dimensions of the cylindrical part of the focusing-lens caustic. The small decrease of the SW dimension in the stationary part of the process (frames 4 - 6) are due precisely to the screening of the radiation as a result of absorption in the plasma.

relations (2) and (4), we obtain

$$\frac{P}{d} = \sqrt{\frac{\rho_0 v_0 v_1}{2(\gamma + 1)\rho_2}} \sim \frac{\text{const}}{\sqrt{p_\infty}}. \qquad (5)$$

The experimental plot of $R(p_\infty)$ shown in Fig. 3, coincides with Eq. (5) in the region $p_\infty \leq 0.5$ atm. In the pressure interval 0.5 - atm, the dependence of R on p_∞ is stronger. This can apparently be attributed to the decrease of v_1 at high pressures compared with the maximum value 1750 m/sec.

Experiment shows also that the SW dimension R increases with increasing diameter of the irradiated spot; this increase is predicted by relation (5).

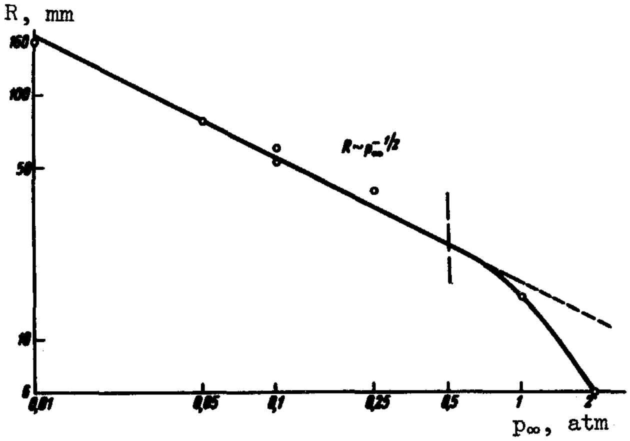

Fig. 3. Dimension R of immobile SW at the beginning of the stationary part of the process vs. the external process. The ordinate scale is logarithmic.

The gasdynamic picture of motion described above for bismuth holds also for other metals. In particular, an immobile SW of a shape similar to that of bismuth was observed by us in analogous experiments on aluminum[3].

The experimentally determined characteristics of an immobile SW make it possible to determine the particle density and the temperature behind the SW front, and therefore to interpret the phenomena connected with absorption of laser radiation by metal vapor (in particular the effect observed by us, of detachment of a plasma jet from the surface of the target at $p_\infty = 2.6$ atm).

The performed experiments make it also possible to the conditions at the target (p_0, T_0, ρ_0, and v_0). The temperature T_0 on the surface of bismuth (at $p_\infty < 1$ atm) turns out apparently to be higher than critical. These results will be published.

In conclusion, the authors thank O. N. Krokhin for pointing out [3], where initiation of a shock wave in an individual spike of a ruby laser was observed (radiation energy of several Joules).

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