NUMERICAL MODELING OF LASER SHOCK WAVES IN CONDENSED MEDIA

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High power laser pulses are a promising tool for carrying out studies in dynamic high pressure physics [1]. Experiments already performed on laser shock wave generation have significantly expanded the range of attainable pressures as compared to classical technology employing chemical explosives or driver devices [1, 2]. Moreover, the laser method differs significantly from traditional techniques in that the high energy concentrations attainable can provide new data on extremal states of materials. However, the process of laser shock wave formation in solids, especially in its initial stages, is still less well studied than the dynamics of plasma flares and compression of thermonuclear targets. The nature of differences in the character of shock wave processes at various radiation intensities as well as the degree of influence of the absorptive properties of the laser plasma remain unclear. In connection with that fact it is of interest to perform a numerical modeling of formation and propagation of laser shock waves in condensed media for a wide range of radiation intensities.

1. We will consider normal irradiation of an opaque obstacle by nanosecond laser pulses in the intensity range $q \simeq 10^8$-10^{13} W/cm^2. For simplicity we will limit ourselves to the planar one-dimensional case. With consideration of elastoplastic properties, the system of equations describing the nonsteady state motion of the plasma formed and shock compression of the irradiated target material has the form

$$\frac{1}{\rho} = V = \frac{\partial x}{\partial m}, \quad m = \int\limits_0^x \rho\, dx, \quad \frac{\partial u}{\partial t} = -\frac{\partial}{\partial m}(p - \sigma_1), \quad u = \frac{\partial x}{\partial t}, \tag{1.1}$$

$$\frac{\partial E}{\partial t} = -(p - \sigma_1)\frac{\partial V}{\partial t} - \frac{\partial q}{\partial m}, \quad \sigma_1 = \frac{4}{3}\mu \ln(V/V_0), \quad \sigma_2 = -\frac{2}{3}\mu \ln(V/V_0),$$

$$\frac{\partial q}{\partial m} = -\varkappa q, \quad V_0 = V(m, 0).$$

Here ρ is density; V, specific volume; p, pressure; u, velocity; σ_1, σ_2, components of the stress deviator defined for the condensed phase [3]; E, specific internal energy; κ, laser radiation absorption coefficient; μ, Lamé constant; x, m, linear and mass coordinates; and t, time. To describe the transition through the elastic limit and plastic flow we use the Mises flow condition [3] $\sigma_1^2 + 2\sigma_2^2 \leq (2/3)\sigma_0^2$ (where σ_0 is the yield point for simple extension).

System (1.1) is written with the supposition of a small contribution from light pressure as well as neglect of energy transport due to thermal conductivity and nonequilibrium effects [2]. The latter can easily be estimated from the expression for the thermalization time [2, 4] $t_{ei} \approx 25(A/z^2) \times (T^{3/2}/n)$, whence, for example, in an aluminum target (A = 13) it follows that at characteristic temperatures $T = 10^4$-10^5 K and electron concentrations $n = 10^{19}$-10^{23} cm^{-3}, corresponding to the state of the absorbing plasma in front of the solid, t_{ei} is of the order of magnitude of 10^{-10}-10^{-16} sec, which is less than the duration of the laser pulses considered here. Note that in Eq. (1.1) radiation reflection from the target is also neglected, since for characteristic problem parameters it comprises less than 10% of the total energy [5].

It is well known [4] that in metals laser radiation is attenuated by a factor of ~10^5 times within a depth of the order of the radiation wavelength λ, whence it follows that complete absorption the radiation energy in the intensity range of interest here will occur within a depth of $x \sim 2\lambda$. In reality the size of the heated layer will be somewhat larger, since up to a time of the order of 10^{-10} sec the thermal wave moves ahead of the compression

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wave [6]. Therefore for the laser pulses with duration $\tau > 10^{-10}$ sec considered here the depth of the absorbing layer can be taken equal to $(2\text{-}3)\lambda$.

We will further assume that plasma formation occurs due to surface evaporation of material (in the early stages of the process) as well as volume sublimation, when as energy concentration increases the lattice binding energy is exceeded. The kinetics of surface evaporation can be described by the well-known Knudsen layer model [6, 7], according to which one can write an expression for the flow parameters on the external boundary of the transition layer between gas and condensed medium in the form

$$\rho_1 = \rho_S F_1(M), \quad T_1 = T_s F_2(M), \tag{1.2}$$

where T_S is the temperature of the target surface; $\rho s(T_S)$ is the saturated vapor density at temperature T_S, defined by the Einstein model of the solid [6]; $F_1(M)$ and $F_2(M)$ are functions of the Mach number M on the external boundary of the Knudsen layer, the precise form of which for evaporation into the medium and counterpressure is presented in [7].

The equation of state and laser radiation absorption coefficient were taken in the form

$$p = p(\rho, E), \quad T = T(\rho, E), \quad \varkappa = \varkappa(\rho, E), \tag{1.3}$$

which together with Eq. (1) and conditions (1.2) completes the problem.

2. For numerical solution of Eq. (1.1) we will use the calculation scheme described in detail in [8], modified here to the case of flows of absorbing laser plasma with consideration of elastoplastic effects in the target. In fact the numerical scheme in Lagrangian variables [8] allows calculation of the flow parameters in both the gas and in the solid, tracking the moving contact boundary. However in its standard variant this technique does not allow modeling of the target surface evaporation process due to the absence of mass exchange between the computation cells. Therefore a special algorithm was developed for solution of the present problem, which considers mass exchange on the phase boundary. The unique feature of this algorithm is that each step in time is divided into two stages: in the first effects related to local mass exchange are considered and intermediate hydrodynamic parameter values are calculated in the cells and on the phase boundary; in the second (Lagrangian) stage system (1.1) is solved and the final values of the unknown parameters in the new time step are determined for the entire integration region. The following operations are performed in the first stage:

a) determination of vapor parameters on the external boundary of the Knudsen layer. Temperature and density are calculated with Eqs. (1.2); pressure and specific internal energy, from the corresponding equations of state, while the characteristic [7] serves as an insufficient condition for velocity (Mach number) determination. Since in this case the pressure itself depends upon M this stage is implicit and it becomes necessary to use a successive approximation algorithm;

b) determination of the mass of vapor intersecting the boundary between condensed and gaseous cells;

c) determination of intermediate flow parameter values in the boundary cells using conversation laws.

If the pressure on the Knudsen layer boundary proves less than that in the gas cell, mass exchange does not occur and the entire calculation process is limited to the Lagrangian stage. Note that the mass exchange stage does not place additional limitations on the time step, since the condition of nonintersection of a single cell volume by the surface evaporation products corresponds completely to the Courant condition [8] used in the calculations.

An important advantage of the proposed method is the possibility of considering a wide range of regimes: from the evaporative, where the quantity of laser radiation energy supplied is equal to or much more than the energy removed by the evaporation products, to processes equivalent to explosion of an intensely superheated surface layer, with the temperature increase due to energy absorption dominating over cooling upon expansion.

3. In performing the calculations special attention was given to the unique features of laser shock wave formation in the target at various radiation intensities. Aluminum was chosen for the material to be modeled, with the equation of state in the form proposed by Tillotson [9]:

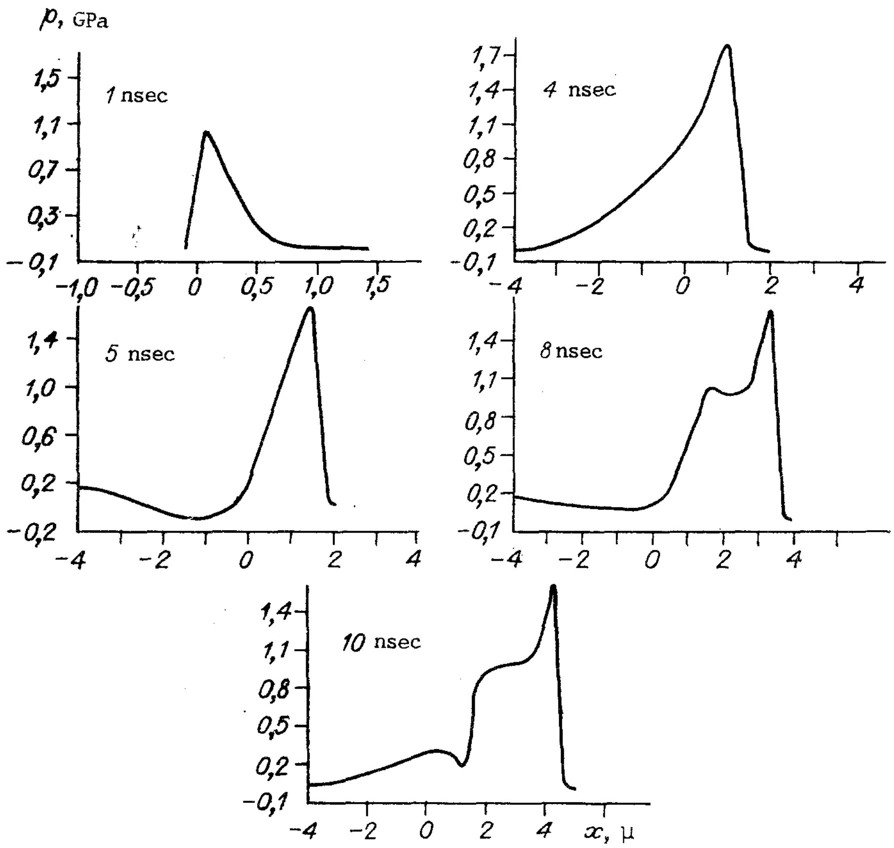

Fig. 1

$$p = A\left(\frac{\rho}{\rho_0} - 1\right) + B\left(\frac{\rho}{\rho_0} - 1\right)^2 + \gamma\rho(E - E_0). \tag{3.1}$$

Here A, B are parameters of the material; ρ_0, E_0 are the density and specific internal energy under normal conditions. The constants in the expression for the Grüneisen coefficient

$$\gamma(\rho, E) = a + \frac{b}{(E/E_0)(\rho_0/\rho)^2 + 1}$$

were chosen to insure continuous transition from the condensed medium to the gas. Temperatures of the plasma and condensed material were determined by approximate expressions of the type $T = C\rho^n E^k$, constructed using tabular data from [10] and an experimental temperature dependence of enthalpy for aluminum [11]. Proper choice of the parameters C, n, k insured continuous transition from one phase region to the other with consideration of energy losses to fusion and evaporation. The form of the absorption coefficients as functions of the density and temperature $\kappa = \kappa(\rho, T)$ for wavelengths 0.35 and 1.06 μm were taken from [12] and [13]. The equations of state were taken from the tables of [14].

It should be noted that in regions where the critical electron concentration was attained complete absorption of the laser radiation was assumed, as is done in calculations of laser compression of shells [4, 15] (radiation of the wavelengths considered penetrates into a plasma of solid state density $n \simeq 10^{21}$-10^{22} cm^{-3}).

Figure 1 shows compression wave profiles at various moments for action of a triangular laser pulse with 10 nsec front and total duration of 30 nsec. Maximum radiation intensity $q = 5 \cdot 10^8$ W/cm^2, wavelength $\lambda = 0.35$ μm, with surrounding air pressure $p_0 = 1.33$ Pa. The ordinate indicates total negative stress, equal to $-(p - \sigma_1)$. It is obvious that in the initial period (up to ~1 nsec) motion of the material is practically lacking and the thermal stress profile is close to an exponential energy liberation profile. Thereafter expansion of the more heated external layers leads to deformation of the compression wave with a quite steep profile directed toward the target. Around the surface there appears a region with

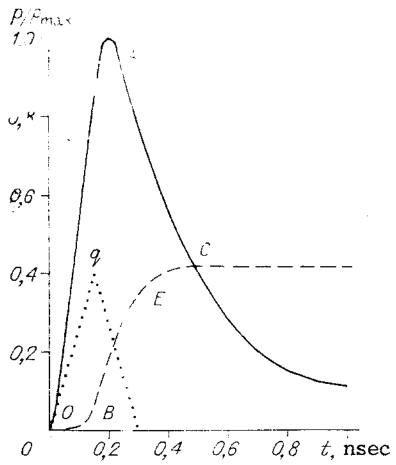

Fig. 2

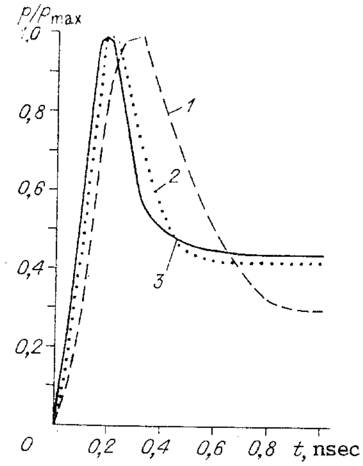

Fig. 3

negative stresses, which indicates the possibility of development of face fracture (since it was assumed in the calculations that negative stress corresponds to extension). However in the case under consideration the momentum of the vapor and the continuing heating do not allow this process to develop completely. It is interesting that the radiation parameters at which face fracture is possible agree well with those predicted in [16]. Thereafter negative stresses disappear, and a second maximum appears in the profile, located in the heated surface zone, because the radiation intensity continues to increase. Increase in temperature and density of the evaporation products with continued surface heating leads to development of absorption "flares" in the vapor, accompanying an abrupt decrease in the fraction of radiation reaching the target. The laser energy almost completely ceases supporting the compression wave, the further motion of which can be considered adiabatic. However, the latter may not be true if the irradiation regime or conditions are changed. For example, clarification of the vapor may significantly change the flow pattern.

We will now consider more intense regimes where aside from thermal stress and the momentum of the released vapor yet another very significant factor appears – volume sublimation and explosive ejection of the absorbing layer. In this case the pressure in the sublimation products will be determined by the third term in Eq. (3.1), $p \sim \rho E$, while the main contribution to pressure in the unheated condensed material is produced by the first two terms, which are proportional to the degree of compression ρ/ρ_0. Thus, two regions can be distinguished: the dense plasma of the volume sublimation products, and the near-surface region of target material which is not completely heated and where pressure dynamics are determined by the laser shock wave formation process. The change in pressure in these regions during action of a triangular radiation pulse with 0.15 nsec front and 0.3 nsec total duration is shown in Fig. 2. Maximum pulse intensity $q = 10^{11}$ W/cm^2, surrounding medium pressure 1.33 Pa, radiation wavelength 1.06 μm. The ordinate shows current pressure referenced to the maximum value p_{max}. The solid line corresponds to the plasma region and the dashed one, to the condensed material, while the dotted line indicates the laser pulse form. Pressure increase continues in the absorbing layer until heating of the material dominates over its cooling due to expansion (segment OA). Before intense expulsion of plasma begins, only elastic stresses are found in the cold material (segment OB), after which an abrupt increase in compression and corresponding increase in pressure occur (segment BE). Having reached some saturation value, caused by inclusion into the compression wave of new volumes of material, the growth of pressure in the cold material slows. At the point C the pressures in both regions become equal and the process of compression of the target by expanding plasma ceases. This time can be considered the final moment of laser shock wave formation. For the calculations performed its onset exceeds the duration of the radiation pulse by a factor of 2.5-4 times. Subsequent shock wave propagation in the target will be controlled by the properties of the material, the target geometry, and the effect of the free boundaries. For converging shock waves, either spherical or cylindrical, intensification with depth is possible due to cumulation effects [17]. In the remaining cases the shock wave will attenuate, but much more slowly than it forms: the characteristic decay time comprises hundreds of nsec or units of μsec.

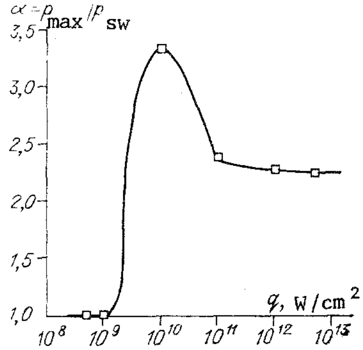

Fig. 4

The higher the laser radiation intensity the more rapidly plasma expansion begins, the earlier maximum pressure is attained in the plasma, and the quicker the shock wave is formed in the target. This can be explained by the increasing velocity of material motion with increase in intensity q. This tendency is illustrated by Fig. 3, where the dynamics of the process considered in Fig. 2 are shown for q = 0.01, 0.1, 1 TW/cm^2 (lines 1-3). The pulse form and other conditions are the same as previously, while the ordinate axis shows current pressure normalized to the corresponding p_{max}. Note that the time required for shock wave formation in the target decreases with increase in q only to a certain limit. Calculations show that the form of the time dependence of p/p_{max} for $q = 10^{13}$ W/cm^2 practically coincides with the analogous curve for $q = 10^{12}$ W/cm^2, shown in Fig. 3. This is due to the impossibility of infinitely high material particle acceleration and the existence of some minimum time limit required for overcoming inertia.

An important parameter characterizing the various regimes is the ratio of the maximum plasma pressure p_{max} to the pressure in the front of the developing shock wave p_{SW}. The dependence of the parameter $\alpha = p_{max}/p_{SW}$ upon intensity of radiation at $\lambda = 0.69$ μm is shown in Fig. 4. For moderate intensity levels ($q \lesssim 10^9$ W/cm^2) α is close to unity, which allows us to consider the target incompressible and to characterize the effect on the target by the momentum delivered to the vapor. Increase in q to 10^{10} W/cm^2 produces a sharp growth in α by a factor of three times. This indicates transition to a regime wherein significant compression of the target material is possible during the process of ejection of the sublimed surface layer. Considering the character of the effects produced this regime could be called a laser contact explosion. At still higher q the parameter α decreases and stabilizes at a level of ~2.3, which is again explained by increase in velocity of sublimation product ejection with increase in q. The higher this expulsion velocity the steeper the segment BE of Fig. 2, and consequently the intersection of the latter with the segment AC occurs at higher pressure. Therefore for $q = 10^{11}$ W/cm^2 the ratio p_{max}/p_{SW} proves to be somewhat lower than for $q = 10^{10}$ W/cm^2. As has already been noted, further increase in q is accompanied by stabilization of the form of the time dependence of p/p_{max} (see Fig. 3) and thus, stabilization of α.

Thus, the parameter α can always be used to evaluate the pressure in the shock wave front within the target from the known maximum pressure in the plasma flare by using the relationship $p_{SW} = p_{max}/\alpha(q)$ or the converse. We will note that the hydrodynamic pressure in the laser contact explosion regime exceeds the elastoplastic portion of the stress tensor by several (for $q = 10^{10}$ W/cm^2) or tens (for $q = 10^{12}$ W/cm^2) of times, while for surface evaporation both these quantities usually lie within the elastoplastic region. Since a change in the elastoplastic properties of a material with an increase in its temperature can have an effect in the latter case in a narrow heated layer given the condition that the thermal portion of the pressure in Eq. (3.1) does not exceed σ_1, the assumption of constancy of the parameters μ and σ_0 proves to be fully justified. The position of the boundary between one and the other regime depends primarily on the depth to which the target surface layer is heated, and thus, on the wavelength of the radiation, as well as the chemical composition and structure of the material. Calculations for aluminum at a wavelength $\lambda = 0.35$ μm show that the corresponding limiting intensity decreases as compared to $\lambda = 1.06$ μm to $\sim 10^9$ W/cm^2.

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