SEMIEMPIRICAL MODEL OF INTERACTION OF ELECTRON BEAMS WITH MATTER

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A simple model of the interaction of strong energy fluxes with materials is described, and the results are compared with experiments and numerical calculations.

The advent of strong energy sources — lasers and electron accelerators — led to the appearance of new problems in metal physics and materials engineering, while in the applied sphere it led to the development of new methods for sizing of materials and welding [1, 2], and it stimulated the study of high-temperature properties of dense media and plasma [3, 4]. Numerical methods give the most complete and detailed information about the interaction process [5, 6], but this requires sorting through a large number of variants. The complexity of such calculations makes it very desirable to have a simplified physical model which is suitable for determining such integral characteristics as the velocity of cutting of the material, the reactive pressure on the cold material, and the intensity of the flow of matter out of the interaction zone. This work is concerned with the description and check of such a physical model.

The processes occurring when a material is exposed to laser and electron beams have some common features. Both cases should therefore be studied within the framework of the same model. The analysis for the electron beam is conducted in a quasi-two-dimensional approximation for $D > \ell$, which for real conditions corresponds to electron energies $E < 10$ MeV. For laser radiation the effective depth of energy liberation is comparable to that for electron irradiation with particle energy $E = 0.1$ keV; this will be demonstrated below.

The action of strong fluxes of laser radiation, creating a wave of surface evaporation, which can be regarded as a surface of discontinuity [1] of physical parameters, was studied previously in [1, 7]. Interpolation expressions for the parameters of laser action with intensity such that losses to evaporation can no longer be neglected are presented in [8]. The result of the action reduces in this case to the expansion of heated vapor. The great contribution of I. V. Nemchinov and his coworkers ([8, 9] and references therein) to the solution of the complicated problem of interaction should be noted. But the employment of the one-dimensional geometry in [8] makes it impossible to extend the computational results to real experimental conditions. Experiments were performed previously for very strong fluxes [10, 11] and a model for the calculation of a number of interaction parameters was presented. The results of [10, 11] agree with the predictions of the theory for the case of strong laser beams [12]. We note that the dependences $P \sim \rho_0^{1/3} q^{2/3}$ found in [10, 11] also follow from dimensional analysis.

Our study of a simplified physical model will be based on the most general assumptions, namely: a) we shall describe the properties of the material by a constant heat capacity c, specific heat of phase transformation λ, and evaporation temperature T; b) the zone of energy liberation will be described geometrically by one characteristic size D, for example, the diameter of the beam or the length of the channel formed; c) because the interaction process is assumed to be stationary a condition is introduced for the average density of the material in the energy liberation zone $\rho = \alpha E/D$. The last condition is predicated on partial or complete evaporation from the side of the cold material and ejection of material from the energy liberation zone. The condition c) can be rewritten as $\rho = \rho_0 D_0/D$ for temperature-independent α. The use of trivial descriptions of the thermophysical properties of materials naturally reduces the potential accuracy of the model, but this is compensated by the fact that the list of materials amenable to analysis is enlarged.

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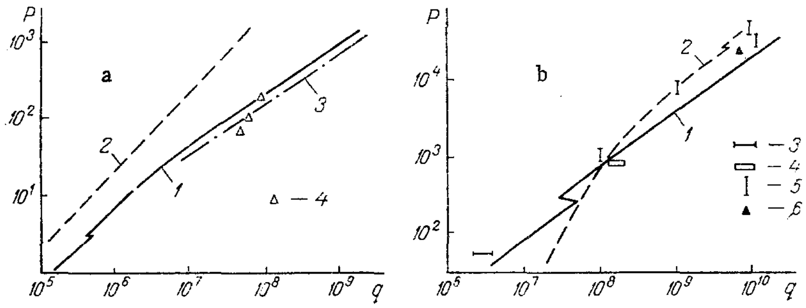

Fig. 1. The pressure on the aluminum versus the intensity of the laser (a) ($\rho = 10^{-4}\ \rho_0$, D = 1 mm) and electron (b) action: a) the curve 1 is calculated from (6) and (7); curve 2 is calculated for the model of surface evaporation [1, 7]; curve 3 corresponds to the one-dimensional hydrodynamic model [8]; 4 are experimental points [8] for different radii of symmetrically irradiated spheres; b) curve 1 corresponds to $\rho/\rho_0 = 10^{-2}$; curve 2 corresponds to $\rho/\rho_0 = 1$; 3 are our measurements; 4 are the measurements of [18]; 5 are the calculations based on the model of [6]; 6 shows the measurements of [19]. P, bar; q, W/cm^2.

The case of laser action reduces within the framework of our approach to the action of electrons with a particle energy of 0.1 keV, which provides a realistic mass range.

The geometric size D introduced above depends, generally speaking, not only on the initial diameter of the beam, but also on the penetrating power of the particles. When electron beams are used in the experiment it can be determined by photographing the energy liberation zone in x rays [11].

We shall write down the hydrodynamic conservation laws for a moving material in the form used in [10] and following from the general conditions at a discontinuity [13]:

$$\rho v = \rho_0 v_0, \tag{1}$$

$$\rho v^2 = P, \tag{2}$$

$$\rho v(\varepsilon + v^2/2) = q. \tag{3}$$

For partial evaporation of the material the internal energy can be represented in the form

$$\varepsilon = \varepsilon(T) + \beta\lambda = cT + \beta\lambda. \tag{4}$$

To solve the system (1)-(3) it is necessary to express ε in terms of P and T. Assuming that the ideal gas relation $\rho_V = P\mu/RT$ holds for the vapor, it can be shown that for the energy liberation zone

$$\beta = \frac{\rho_V(\rho_0 - \rho)}{(\rho_0 - \rho_V)\rho} \approx \frac{\rho_V}{\rho}. \tag{5}$$

Using (4) and (5) and the equation for the density of vapor as an ideal gas, for $P\mu/\rho RT < 1$ (i.e., $\beta < 1$) we have

$$(\rho P)^{1/2}\left(cT + \frac{P\mu}{\rho RT}\lambda + \frac{P}{2\rho}\right) = q. \tag{6}$$

For complete ($P\mu/\rho RT \geq 1$) evaporation of material in the energy liberation zone Eq. (6) transforms into

$$(\rho P)^{1/2}\left(\frac{P}{\rho(\gamma - 1)} + \lambda + \frac{P}{2\rho}\right) = q. \tag{7}$$

The transition from incomplete to complete evaporation is evidently completed when $P = P^* = \rho RT/\mu$. Thus for electrons with energy E = 0.3 MeV and a diameter of the source beam D = 5 mm we have in aluminum P^* = 200 bar.

The entire procedure for approximate calculations reduces to a sequence of operations. Starting from the type of particles (the quantities E and α) and the value of the geometric factor D, we determine the average density of the material in the energy liberation zone, corresponding to the stationary interaction regime. The system of equations (6) and (7)

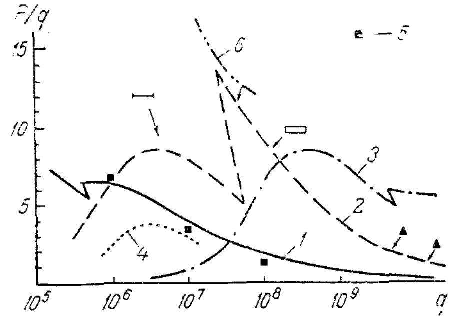

Fig. 2. Measurement of the specific recoil momentum P/q (dyn·sec/J) versus the intensity for aluminum: 1-3) construction based on the proposed model (1 — $\rho/\rho_0 = 10^{-4}$; 2 — 10^{-2}; 3 — 1); 4) experiment for lasers [14]; 5) calculations based on the surface evaporation model [1]; 6) the results of the calculations of [9]. The remaining notation is the same as in Fig 1.

determines P — the pressure at the boundary of the cold material. The expansion velocity of the products v is determined from Eq. (2). The velocity of cutting can be easily calculated from Eq. (1).

Figure 1 shows the curves P(q) for three fixed values of ρ/ρ_0 (1, 10^{-2}, 10^{-4}). The value $\rho/\rho_0 = 10^{-4}$ is characteristic for laser action with D = 1 mm. The same figure shows the results of experimental studies and other calculations.

The breaks in the curves in Fig. 1 at $\beta = 1$ are a result of the change in the description of the internal energy from (6) to (7) and can be smoothed. Here, however, they are retained as an illustration of the accuracy claimed by the model. The figure also marks the points obtained numerically using the procedure of [6]. The experimental measurement of the pressure for $q = 5 \cdot 10^6$ W/cm² was performed on an electron accelerator with energy E = 0.3 MeV with the use of a magnetohydrodynamic pressure gauge.

For high irradiation intensities ($q > 10^8$ W/cm²) the pressure can be calculated based on the asymptotic expression following from Eq. (7):

$$P = (D_0/D)^{1/3}\, \rho_0^{1/3}\, q_0^{2/3}. \tag{8}$$

The functional form of expression (8) agrees with the expression proposed and checked previously [8, 10-12].

The specific recoil momentum P/q, as is well known [1, 12, 13], has a maximum for moderate irradiation intensities. An analogous result follows from our calculations (Fig. 2). This is easily understood, since for small q, $P \sim q^2$ (5), while for large q, as already pointed out, $P \sim q^{2/3}$. Comparison of our results with the experimental results of other authors shows that the computed values of the parameters are somewhat too high (see Fig. 2). This can be explained by the fact that in the experiments the free generation regime, for which the irradiating flux has a pulsating character, is, as a rule, used.

The result obtained from the model is also interesting. The maximum of the specific recoil momentum should be observed, as can be easily shown, for $q \sim (\rho_0 D_0/D)\lambda^{3/2}$. This behavior of P/q versus q is indeed characteristic for laser action [14, 15], while in the regime of gas breakdown near the target [15] a corresponding shift of the maximum toward lower intensities is observed.

We shall study in greater detail the question of the stability (the assumed stationarity) of the interaction process. In the case of laser action the changes in the parameters of the expanding material are correlated with the changes in the intensity of the irradiating flux [1] and the problem of stability reduces to the analysis of the vapor—liquid boundary [16]. For an electron beam, penetrating deep into the material, under prolonged action self-excited oscillations, arising owing to the scattering of particles by vapor in the channel, become significant [2]. The characteristic period of such oscillations can be estimated as $t \sim D/v$. The results of the model studied are, however, applicable also in the case when they are regarded as the result of the corresponding time averaging. In this case the length of the channel created must be taken as the characteristic size.

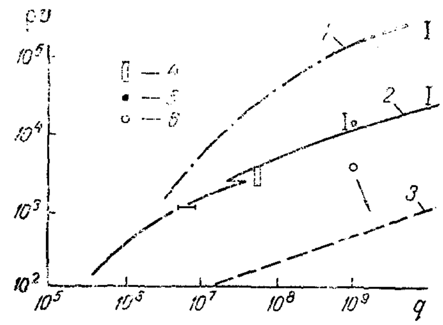

Fig. 3. Rate of mass outflow for aluminum; 1-3) calculation using (6), (7) ($1 - \rho/\rho_0 = 1$; $2 - 10^{-2}$; $3 - 10^{-4}$); 4) measurements of [18] for electron and laser beams, respectively. See Fig. 1 for the rest of the notation. ρv, $g/(cm^2 \cdot sec)$.

The explosive mechanism for ejection of mass from the energy liberation zone, proposed by some authors [17], cannot fundamentally alter the results of the model studied, since the thermodynamic parameters of the proposed nonequilibrium state differ comparatively little from the equilibrium parameters [13], while the nonuniformity of the problem and the hydrodynamics of expansion reduce the effect of overheating to a minimum. The stationary regime is established over a definite time period from the start of irradiation. An approximate method for determining the lag time, taking into account the effect of heat conduction (for the case of surface energy liberation), is presented in [1].

Figure 3 shows the dependence of the rate of mass ejection on the intensity of the irradiation. Starting from the assumptions of the physical model, here we took into account only the primary ejected mass. For very high irradiation intensities, however, the additional ejection of mass could be caused by the action of a shock wave [5, 10], while for low intensities liquid metal can flow out of the energy liberation zone [2]. Analysis of Fig. 3 shows that for deep melting of materials it is advantageous to use particle fluxes with higher penetrating power. The procedure for finding the optimal interaction regimes will be determined by the specific external requirements. Laser beams are preferable for realizing reactive acceleration under low pressures on a surface.

This physical model of the interaction of radiation fluxes with matter, in spite of its simplicity, qualitatively explains existing experimental results. It also makes it possible to evaluate important characteristics of the interaction, such as the reactive pressure owing to the expansion of the products, the average expansion velocity of the products, and the cutting velocity.

NOTATION

D, diameter of the beam; ℓ, effective depth of energy liberation; E, energy of the electrons; q, intensity of the radiation flux; $\alpha = 0.1$ g/cm^2, stopping power [3]; D_0, initial range of the radiation in the material; v, average velocity of the material flowing out of the energy liberation zone; $v_0 = v_C$, cutting velocity; ε, specific energy; P, pressure; β, relative fraction of evaporated material; ρ_0, density of cold material; ρ_V, vapor density; ρ, average density; $\gamma = 1, 2$, adiabatic index; c, heat capacity of the material; λ, specific heat of phase transformation; T, evaporation temperature.

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STRUCTURE OF THE PLASMA FLOW FORMED IN MULTISTREAM MIXING CHAMBERS OF DIFFERENT TYPE

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The results of spectral measurements of the temperatures of an air plasma flow are presented and analyzed.

The most important characteristics of plasma reactors for processing gas-phase stock, solutions, and dispersed materials depend on the parameters of mixing and heat transfer between the plasma flow, the system being treated, and the walls of the reactor channel. In order to intensify the mixing and heat transfer between the systems being treated with the plasma flows and to reduce heat flow into the wall different structures for the plasma reactors are under study. The review and analysis of well-known plasma reactors performed in [1] and subsequent publications show that one of the most widely used and, probably, most promising setups is a plasma reactor based on the multistream mixing chamber.

Studies of mixing chambers — the main element of a plasma reactor — are being conducted along different lines. In one of the latest works [2] the gas-dynamics of a three-stream mixing chamber is studied and it is shown that even without the introduction of the components being treated the plasma flow is characterized by a complex structure, the presence of reverse flows, and in some cases recirculation zones. Heat transfer in a plasma reactor with a three-stream mixing chamber is analyzed in [3-6]. It is shown that the use of cylindrical and conical mixing chambers with radial and tangential injection of the plasma jets [3, 4, 6] makes it possible to regulate the heat flow into the wall of the reactor and thereby affect the efficiency of the entire setup. Control of the plasma flow structure is achieved both by changing the configuration of the chamber itself and by placing plasmatrons at a definite angle to the axis of the plasma unit.

In this connection, aside from determining the gas-dynamic and thermal characteristics of the objects under study, it is desirable to study the temperature distribution over their

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