FORMATION OF AN ELASTIC WAVE IN METAL IRRADIATED BY AN IMPULSIVE ION BEAM

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The exposure of a material to an impulsive ion beam (IIB) leads to rapid heating of the surface layer. This heating in turn creates widely propagated temperature gradients and associated elastic strains. The authors of [1] were the first to study the brittle fracture of solids under the influence of a powerful ion beam and hypothesized that the most likely mechanism by which the beam acted on the material was thermal shock. The authors of [2] calculated the space–time distribution of the mechanical stresses created in metals acted upon by pulsed laser radiation. To adequately interpret experiments conducted to study the effects created in an IIB–material system, it is necessary to take into account the features of the ion beams. Allowance should be made for the fairly high level of complexity and uniqueness of the energy spectrum of beams generated by different methods.

Here we propose to use the group method to solve the given class of problems. This approach makes it possible to numerically model the formation and propagation of a thermoelastic wave in a plane barrier due to the action of an IIB and to analyze the effect of the spectral characteristics on the occurrence of the process which is initiated.

It is assumed that the energy contribution of the ion flow ensures heating of the particle thermalization region in the barrier to a temperature not in excess of the melting point. An appreciable temperature gradient is created on the boundary of this region, while inside the region the thermal component of the pressure is of the same order as the cold pressure [3]. The relatively small magnitude of the mechanical perturbation of the absorbent as a result of the heating makes it possible to limit ourselves to the dynamic problem of thermoelasticity when we attempt to describe the motion of the medium:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + W(x,\ t), \tag{1}$$

$$\frac{1}{C_l^2}\ \frac{\partial^2 U}{\partial t^2} = \frac{\partial^2 U}{\partial x^2} - \frac{\alpha(1+\nu)}{1-\nu}\ \frac{\partial T}{\partial x}, \tag{2}$$

$$0 < x < l, \quad 0 < t < \infty.$$

The value $x = 0$ corresponds to the irradiated surface. The temperature dependence of c, λ, and α was tabulated in accordance with the data in [4]. Values between the nodes of the table were determined by linear interpolation.

The above formulation of the problem is valid for irradiated materials with a linear dependence of stress on strain. For example, the ultimate strength is close to the yield strength for hard silumin (Al–Si), the hard alloy Al–Mg (1.5-2.5%)–Mn (1.2%), duralumin after quenching, aging, and cold-working, tungsten, and beryllium. These materials fracture immediately after elastic deformation or after very little plastic deformation, with the amount of the latter not exceeding the amount of the former in any case [5].

The time of heating in the particle thermalization region is equal to the duration of the radiation pulse and should not be greater than the characteristic time of mechanical unloading $\tau_u \gtrsim R/C_l$, where R is the thickness of the heated layer. Otherwise, thermal stresses fail to develop when stress relaxation takes place as rapidly or more rapidly than the rise in the temperature of the surface layer [6].

The temperature dependence of sonic velocity is determined by the corresponding relations for the density, Young's modulus, and shear modulus of the given material. For example, for tungsten [7], a change in temperature from 280 to 1275°K leads to a reduction in C_l from

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$5.198 \cdot 10^3$ to $5.02 \cdot 10^3$ m/sec (the relative change is 3.8%). In the absence of structural changes in the investigated temperature range, mean values of C_l for metals and alloys can be used with sufficient accuracy.

The initial conditions for system (1), (2) are written in the form

$$T(x,\ 0) = T_0, \quad U(x,\ 0) = \frac{\partial U(x,\ 0)}{\partial t} = 0, \tag{3}$$

where T_0 is the initial temperature of the plate.

The boundary conditions for the heat-conduction equation describe the removal of heat from the surface by radiation in vacuum:

$$\lambda \frac{\partial T(0,\ t)}{\partial x} - \varepsilon\sigma T^4(0,\ t) = 0, \quad \lambda \frac{\partial T(l,\ t)}{\partial x} + \varepsilon\sigma T^4(l,\ t) = 0. \tag{4}$$

A good approximation of a perfectly flexible boundary is the boundary with a vacuum [8]. The total reflection of the elastic wave from the specimen boundary which corresponds to this approximation is described by the equations

$$\begin{aligned} \frac{\partial U(0,\ t)}{\partial x} &= \frac{\alpha(1+\nu)}{1-\nu}[T(0,\ t) - T_0], \\ \frac{\partial U(l,\ t)}{\partial x} &= \frac{\alpha(1+\nu)}{1-\nu}[T(l,\ t) - T_0]. \end{aligned} \tag{5}$$

Using a finite-difference approximation of the partial derivative of the function $\Theta_j(x)$ with respect to x and introducing the notation $b = (\Delta x)^{-1}$, we write a multigroup system of ion transport equations on a uniform coordinate grid in a "straight-forward" approximation:

$$\begin{gathered} b\Phi_j^k + \Sigma_{\mathrm{tot}\,j}^k \Phi_j^k - \sum_{l=j}^{N} \Sigma_{in}^k (l \to j)\, \Phi_l^k = b\Phi_j^{k-1}, \\ j,\ l = 1,\ 2,\ 3,\ \ldots,\ N; \quad k = 1,\ 2,\ 3,\ \ldots,\ K. \end{gathered} \tag{6}$$

Here

$$\begin{gathered} \int_{E_{j-1}}^{E_j} \Sigma_{in}^k (E' \to E)\, dE = \Sigma_{in}^k (l \to j), \quad E_{l-1} < E' < E_l, \\ \Sigma_{\mathrm{tot}\,j}^k = \sum_{m=1}^{j-1} \Sigma_{in}^k (j \to m) \end{gathered} \tag{7}$$

are the macroscopic cross section of the inelastic interaction of the ion beam with an atom (ion) of the absorbent, with the transition from the l-th to the j-th energy group, and the macroscopic cross section for removal from the j-th group, respectively, and

$$\Phi_j^k = \int_{E_{j-1}}^{E_j} \Phi^k(E)\, dE$$

is the flux of particles of the j-th energy group.

System (6) can be conveniently written in matrix form:

$$\Sigma^k \Phi^k = B^{k-1}, \tag{8}$$

where

$$\Phi^k = \begin{bmatrix} \Phi_1^k \\ \Phi_2^k \\ \Phi_3^k \\ \vdots \\ \Phi_N^k \end{bmatrix} \qquad B^{k-1} = \begin{bmatrix} b\Phi_1^{k-1} \\ b\Phi_2^{k-1} \\ b\Phi_3^{k-1} \\ \vdots \\ b\Phi_N^{k-1} \end{bmatrix}$$

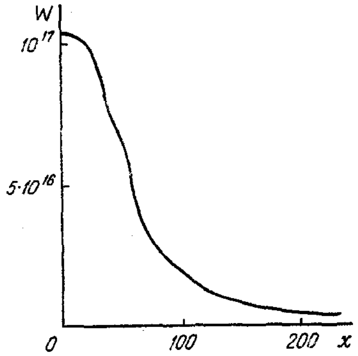

Fig. 1. Power density. W, W/m³; x, μm.

are N-dimensional vectors; Σ^k is a square matrix of the N-th order. The elements of Σ^k are determined by the expressions:

$$\Sigma^k_{mn} = b + \Sigma^k_{\text{tot}\,n} - \Sigma^k_{in}(n \to m) \quad \text{at} \quad n = m,$$

$$\Sigma^k_{mn} = -\Sigma^k_{in}(n \to m) \quad \text{at} \quad m < n,$$

$$\Sigma^k_{mn} = 0 \quad \text{at} \quad m > n.$$

The value of $b = (\Delta x)^{-1}$ is taken equal to the maximum of the macroscopic removal cross sections $\Sigma^k_{\text{tot}\,n}$, n = 1, 2, ..., N, k = 2, 3, ..., K. The values of $\Theta_j{}^k$ for each k = 2, 3, ..., K are determined from known $\Theta_j{}^{k-1}$ from solution of algebraic system (8) by the Gauss method. The superscript k = 1 corresponds to the left (irradiated) boundary of the plate. In the calculations, the energy range (0-8.5) MeV was broken down into 20 equal intervals. The spectrum of the protons in the beam ($\Theta_j{}^1$) corresponded to the results in [1]. The function W(x, t) was determined by the relation:

$$W(x, t) = \tau(t) \sum_{j=1}^{N} Q_j(x)\Phi_j(x), \tag{9}$$

where

$$Q_j(x) = \sum_{m=1}^{j=1} \Sigma_{in}(j \to m, x)\overline{Q}(j \to m), \quad \tau(t) = \begin{cases} 1, & 0 < t \leqslant \tau_p, \\ 0, & \tau_p < t. \end{cases}$$

The duration of the radiation pulse was assumed to be equal to τ_p = 40 nsec and did not exceed the characteristic stress relaxation time $\tau_u \approx 50$ nsec.

Figure 1 shows the dependence of the power released on the coordinate (in a beryllium plate) calculated for the case of a proton beam obtained by the method of collective acceleration.

We used implicit systems of second-order finite-difference equations to numerically solve Eqs. (1), (2) with corresponding initial and boundary conditions (3), (4). The choice of integration interval with respect to the time Δt and the coordinate Δx can be arbitrary, since the systems are "unconditionally stable" [9]. Figure 2 shows the family of curves reflecting the space-time evolution of the mechanical stress field in a plate irradiated by an IIB.

It can be seen from Fig. 1 that the power density correlated well with features of the proton spectrum if we analyze the results in a one-frequency approximation. The density of beam current, j ≈ 11 A/cm² [1], makes it possible to study the process of interaction with a material without allowance for collective effects. In principle, the group method is more flexible in regard to the need to consider the mutual effect of particles during deceleration than any other method, thus making it possible to investigate the given range of problems.

The dependences of the mechanical stresses (Fig. 2) on time and the coordinate reflect the fact that by the end of the pulse, the maximum compressive stresses have developed in the thermalization region of ions which are most representative in the beam spectrum. A rarefaction wave is formed at the irradiated surface and moves at the velocity C_l toward the right boundary. Its amplitude increases nonlinearly up to the moment corresponding to the moment of the current pulse. Given the above parameters of the proton beam, neither the

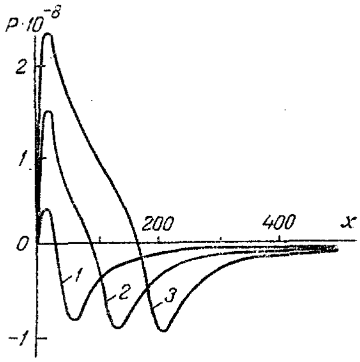

Fig. 2. Mechanical stress field in the plate: 1) t = 10 nsec; 2) 25 nsec; 3) 40 nsec; P, N/m^2; x, μm.

compressive nor the tensile stresses exceed the static ultimate strength of beryllium $\sigma_u = 4.8 \cdot 10^8$ N/m^2 [4].

The method developed here makes it possible to calculate the mechanical stresses in brittle materials for realistic ion-beam parameters. It can be used to study shock-wave processes initiated by the action of powerful ion beams on high-melting materials with a high ultimate strength. The main advantage of the proposed method is its universality in regard to the type of particle beam used.

NOTATION

T, temperature; W(x, t), energy released per unit time per unit mass of material of the barrier; U, strain; ρ, c, λ, density, heat capacity, and thermal conductivity of the material, respectively; C_l, longitudinal sonic velocity; α, ν, coefficient of linear expansion and Poisson's ratio; l, thickness of plate; τ_p, duration of radiation pulse; ε, σ, emissivity and Stefan–Boltzmann constant; Θ, ion flux; E, energy of ion; Σ, macroscopic cross section; τ(t), time function; $\overline{Q}(j \to m)$, mean value of energy lost by ion in the transition from group j to group m; Q_j, energy released per unit segment during the passage of group-j ions; x, space coordinate; t, time. Indices: p, impulse; k, number of node of three-dimensional integration network; j, l, m, n, number of a specific energy group; N, total number of energy groups; K, number of nodes of network; tot, total.

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